A LONG TERM VOLTAGE STABILITY ANALYSIS USING DYNAMIC LOAD MODEL

A Thesis Submitted

in Partial Fulfillment of the Requirements

for the degree of

Master of Technology

By

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to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

March 2000

Dedicated to

my parents

Certificate

It is certified that the work contained in the M.Tech thesis entitled **A LONG TERM VOLTAGE STABILITY ANALYSIS USING DYNAMIC LOAD MODEL,** by *Chauhan Kalpesh Ishwarbhai* has been carried out under the joint supervision of myself and Prof. A. M. Miri of University of Karlsruhe (TH), Germany and that this work has not been submitted elsewhere for a degree.

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We hereby certify that the work contained in the master thesis entitled

"Long-Term Voltage Stability Analysis Using Dynamical Load Modelling"

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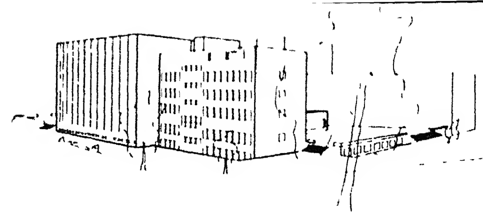

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Abstract

Due to the stressed operation of the power system, the power utilities are facing the problem of voltage security and voltage instability. A power system becomes more imminent to voltage instability due to the outage (contingency) of any branch of its transmission network.

Appropriate modeling of loads is of primary importance in voltage stability studies. This thesis deals with the modeling of loads consisting of static as well as dynamic load models. The impact of different load models on the voltage stability has been compared. In addition, the effect of over excitation limiter (OXL) and transformer under load tap changer (ULTC) on the voltage stability are also investigated along with the different load models. Dynamic analysis provides most accurate replication of the time response of the power system. Accurate determination of the time sequence of the different events leading to system voltage instability is essential.

Two power system networks, one a 11-bus test system and the other 39-bus New England test system have been chosen for the case studies and long-term dynamic analysis have been carried out. The simulations have been done with the NETOMAC (NEtwork TOrsion MAchine Control) software developed by Siemens AG, Germany. The simulation results show that following the outage of transmission line, voltage collapse can be observed with the long-term dynamic effects of ULTC and OXL. Incorporation of different load models leads to different voltage stability scenario.

Acknowledgements

First of all, I would like to thank DAAD for considering me suitable for its fellowship under sandwich program and giving me such a nice opportunity to pursue M.Tech thesis work in Germany.

I would like to thank my thesis supervisor Prof. S.C. Srivastava and Prof. A. M. Miri to give me an opportunity to work under him and allowing me to do thesis under DAAD exchange program.

I am greatly indebted to my German instructor Prof.-Ing A. M. Miri to inspire me during my thesis work. I thank Dipl.-Ing Micheal Merkle for helping me during my thesis work. I owe sincere thanks to my colleagues Muller Cartsan, Janya, Willy, Gabi, Jochen and entire staff at the Institute of Electrical Energy System and High Voltage Technology. Support from Siemens AG, Germany regarding software problem is greatly acknowledge. I can not forget the company of Karthik and Vivek during my stay at karlsruhe, Germany.

I cannot forget the great time, I had with my friend Bhunnu with whom I shared many of my deepest feelings. The company of T.Muralikrishna and Dipan can not be forgettable. I had great time being with Ullash, Tulasi, Prasad, Jagdish, Jaine, R. K. Verma, Parveenkumar and Raja who were my classmates.

The homely atmosphere at the home of Bhavanaben and her family is gratefully acknowledge.

Finally, words do not suffice to express my indebtedness and the deep affection I have for my parents and my sisters Kalu and Munni, for they have been my source of inspiration and moral support.

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Abbreviations

OXL → Over Excitation Limiter
LTC → Load Tap Changer
ULTC → Under Load Tap Changer
CARP → Constant Active and Reactive Power
GDLM → Generic Dynamic Load Model

CHAPTER 1

INTRODUCTION

1.1 General

Electric utilities have been forced in recent years to transfer the maximum possible power through existing networks due to a variety of limitations in the construction of new generation and transmission facilities. Voltage stability problems normally occur in such heavily stressed systems.

It is now considered as a major concern in planning and operating electric power systems. More and more electric utilities are facing voltage stability imposed limits. Voltage instability and voltage collapse have resulted in several major system failures (blackouts), such as,

- New York Power Pool disturbance of September 22, 1970
- French System disturbance of December 19, 1978 and January 12, 1987
- Northern Belgium system disturbance of August 4,1982
- Florida System disturbance of December 28, 1982
- Swedish system disturbance of December 27, 1983
- The massive Tokyo blackout in July 23, 1987

According to Ref. [1], voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all nodes in the system under normal and contingent conditions. A system enters a state of voltage instability when a

disturbance, increase in load demand, or change in the system condition causes a progressive and uncontrollable decline in voltage. One of the main factors causing the instability is the inability of the power system to meet the demand for reactive power.

A criterion for voltage stability is that, for a given operating condition at every bus in the system, the voltage magnitude increases as the reactive power injection at the same bus is increased. A system is voltage unstable if, for at least at one bus in the system, the bus voltage magnitude decreases as the reactive power injection at the same bus is increased. In other words, a system is voltage stable if V-Q sensitivity is positive for every bus and voltage unstable if V-Q sensitivity is negative for at least one bus. Voltage stability will remain a challenge in the foreseeable future and, indeed, is likely to increase in importance. One reason is the need for more intensive use of available transmission facilities. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system. In addition to the inadequate strength of the transmission network and power transfer levels, the principal factors contributing to the voltage collapse are the generator reactive power or voltage control limits, load characteristics, characteristics of the reactive compensation devices and the action of the voltage control devices such as transformer under load tap changers(ULTCs) etc.

It is still a fresh subject and many advances in understanding, simulation software, and on-line security assessment software are likely to be developed in future years. In view of this, it is worthwhile illustrating some of the basic concepts related to voltage stability, which are given in subsequent sections.

1.2 Time Scale and Contributing Factors

1.2.1 Time scale

Voltage collapses can take place on the following time scales ranging from seconds to hours.

(1) Electromechanical transients (e.g. generators, regulators, induction machines) and power electronics (e.g. SVC, HVDC) in the time range of seconds.

(2) Discrete switching devices, such as load tap changers and excitation limiters acting at intervals of tens of seconds.

(3) Load recovery processes spanning several minutes.

For voltage stability studies, time scale 1 is called the transient time scale. Time scales 2 and 3 constitute the so called "long term" time scale for voltage stability analysis (in the past, this long term time scale was sometimes called "midterm"). Electromagnetic transients on transmission lines and synchronous frequency transients such as DC component of short circuit currents occur too quickly to be important in voltage collapse. It is assumed that all electromagnetic transients die out so fast that a sinusoidal steady state remains and one can analyze voltages and currents as time varying quantities. Increase in load over a time scale of hours can be significant in voltage collapse. Figure 1.1 outlines a power system model relevant to voltage phenomena, which are decomposed into transient and long-term time frames.

Voltage collapses can be classified as occurring in transient time scales alone or in the long term time scale. Voltage collapses in the long term time scale can include effects from the transient time scale; for example, a slow voltage collapse taking several minutes may end in a fast voltage collapse in the transient time scale.

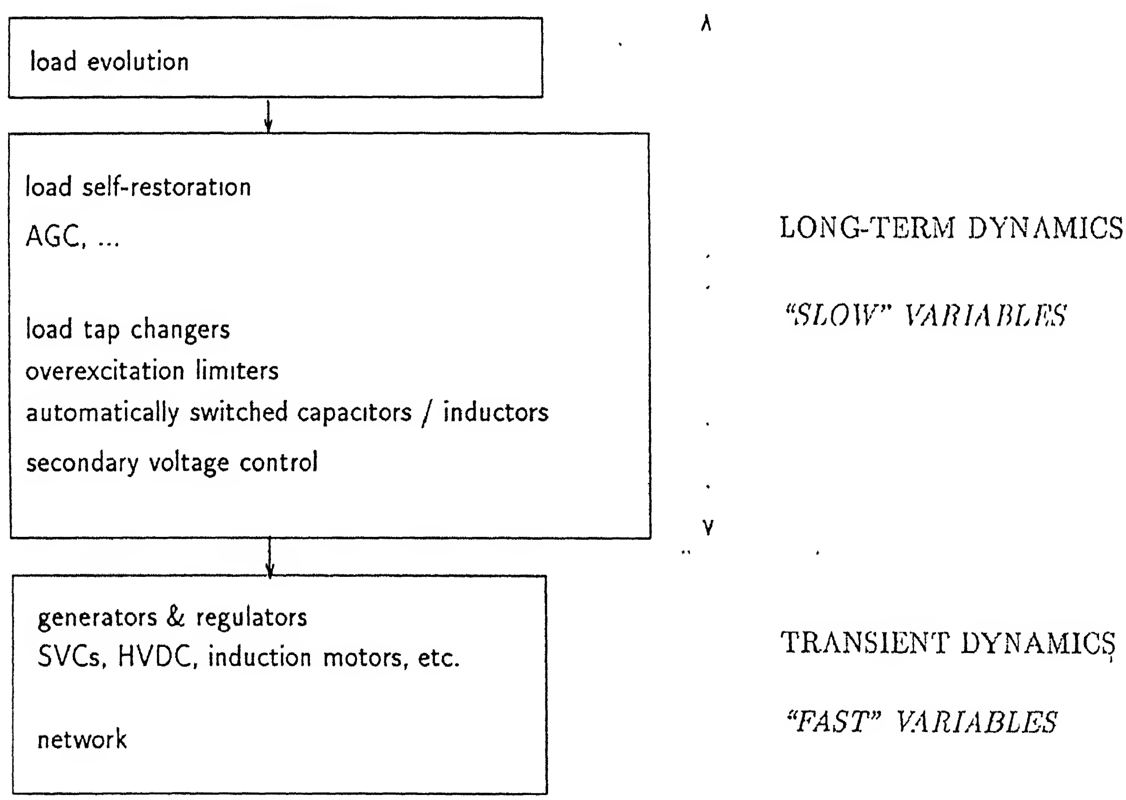

FIG 1.1 Voltage collapse time scales

1.2.2 Reactive power and voltage collapse

Voltage collapse typically occurs on power systems which are heavily loaded, faulted and/or have reactive power shortages. Voltage collapse is a system instability in that it involves many power system components and their variables at once. Indeed, voltage collapse often involves an entire power system, although it usually has a relatively larger involvement in one particular area of the power system. Although many other variables are typically involved, some physical insight into the nature of voltage collapse may be gained by examining the production, transmission and consumption of reactive power. Voltage collapse is associated with the reactive power demands of loads not being met because of limitations on the production and transmission of reactive power. Limitations on the production of reactive power include generator and SVC reactive power limits and the reduced reactive power produced by capacitors at low voltages. The primary limitations on the transmission of reactive power are the high reactive power loss on heavily loaded lines and line outages. Reactive power demands of loads increase with load increases, motor stalling, or changes in load composition such as an increased proportion of compressor load.

1.2.3 Changes in power system contributing to voltage collapse

There are several power system changes known to contribute to voltage collapse.

(a) Increase in loading.
(b) Generators or SVC reaching reactive power limits.
(c) Action of tap changing transformers.
(d) Load recovery dynamics.
(e) Line tripping or generator outages.

Most of these changes have a large effect on reactive power production or transmission. Control actions such as switching in shunt capacitors, blocking tap changing transformers, redispatch of generation, rescheduling of generator and secondary voltage regulation, load shedding and temporary reactive power overload of generators are countermeasures against voltage collapse.

1.2.4 Stability and voltage collapse

To discuss voltage collapse some notion of stability is needed. One of the useful definitions is small disturbance stability of an operating point.

"An operating point of a power system is small disturbance stable if, following any small disturbance, the power system state returns to be identical or close to the predisturbance operating point."

This definition describes the dynamic behavior of the power system when a small disturbance occurs. A power system operating point must be stable in this sense to be sustainable in practice.

Suppose a power system is at a stable operating point. It is routine for one of the changes discussed above to occur and the power system to undergo a transient and restabilize at a new operating point. If the change is gradual, such as in the case of a slow load increase, the restabilization causes the power system to track the operating point as the operating point gradually changes. This is the usual and desired power system operation.

Exceptionally, the power system can lose stability when a change occurs. One common way in which stability is lost in voltage collapse is that the change causes the operating point to disappear. No operating point implies that the power system undergoes a transient. The dynamic fall of voltages in this transient can be identified as a voltage collapse. The transient collapse can be complex, with an initially slow decline in voltages, punctuated by further changes in the system followed by a faster decline in voltages. Thus the transient collapse can include dynamics at either or both of the transient and long-term time scales defined above. Corrective control actions to restore the operating equilibrium are feasible in some cases. Mechanisms of voltage collapse are explained in much more detail in the following sections.

1.2.5 Cascading voltage collapse

Voltage collapse can also be caused by a cascade of power system changes, as for example when a series of large motors stall in succession or when a series of generator reactive power limits are reached in succession. Cascading outages are significant factors in voltage collapse but there are few mathematical techniques

developed to assist in understanding or computing them. The main approach available seems to be working out the sequence of events of each individual cascading outage with assistance from simulations. The more advanced time domain simulations can easily reproduce cascading outages. Also continuation methods have the potential to compute the discrete events of the cascade so that loading margins to collapse can be computed. However, continuation methods do not represent the time dependence of events such as reactive power limits.

1.2.6 Relation with classical transient stability

Although voltage collapse is correctly thought of as significantly involving the dynamic decline of voltage magnitudes, it involves to some extent all the other power system variables. In particular, machine angles are typically involved in the collapse. Thus there is no sharp distinction between voltage collapse and angle collapse or lack of the classical transient stability, and most practical collapses contain some proportion of both voltage instability and angle instability. (Note that the approximate decoupling of real power and angles from reactive power and voltage magnitudes fails under the highly loaded conditions of most voltage collapses.) A "pure voltage collapse" can be regarded as an extreme case whose main use is pedagogical.

The differences between voltage collapse and lack of classical transient stability are those of emphasis: voltage collapse focuses on loads and voltage magnitudes whereas classical transient stability focuses on generators and angles. Also voltage collapse often includes longer time scale dynamics and includes the effects of continuous changes such as load increases in addition to discrete events such as line outages.

1.2.7 Maintaining viable voltage levels

One important problem related to voltage collapse is that of maintaining viable voltage levels. Voltage magnitudes are called viable if they lie in a specified range about their nominal value. Transmission system voltage levels are typically regulated to within 5% of nominal values. It is necessary to maintain viable voltage levels as system conditions and the loads change.

Voltage levels are largely determined by the balance of supply and consumption of reactive power. Since inductive line losses make it ineffective to supply large quantities of reactive power over long lines, much of the reactive power required by loads must be supplied locally. Moreover generators are limited in the reactive power they can supply and this can have a strong influence on voltage levels as well as voltage collapse.

Devices for voltage level control include
(1) Static and switchable capacitor banks
(2) Static Var control
(3) LTC transformer
(4) Generators

A low voltage problem occurs when some system voltages are below the lower limit of viability but the power system is operating stably. Since a stable operating point persists and there is no dynamic collapse, the low voltage problem can be regarded as distinct from voltage collapse. Low voltages and their relation to voltage collapse are now discussed.

Increasing voltage levels by supplying more reactive power generally improves the margin to voltage collapse. In particular, shunt capacitors become more effective at supplying reactive power at higher voltages. However, low voltage levels are a poor indicator of the margin to voltage collapse. Increasing voltage levels by tap changing transformer action can decrease the margin to voltage collapse by in effect increasing the reactive power demand.

There are some relations between the problems of maintaining voltage levels and voltage collapse, but they are best regarded as distinct problems since their analysis is different and there is only partial overlap in control actions which solve both problems.

1.3 Voltage Stability Analysis

1.3.1 Classification of voltage stability

It is helpful to classify voltage stability into two categories: *large-disturbance voltage stability* and *small-disturbance voltage stability*. These subdivisions essentially

decouple phenomena that must be examined by using nonlinear dynamic analysis from those that can be examined by using steady-state analysis. This classification can simplify analytical tool development and application, and it can result in tools that produce complementary information.

Large-disturbance voltage stability is concerned with a system's ability to control voltages following the large disturbances such as system faults, loss of load, or loss of generation. Determination of this form of stability requires the examination of the dynamic performance of the system over a period of time sufficient to capture the interactions of such devices as ULTCs (Under Load Tap Changers) and generator field current limiters. Large disturbance stability can be studied by using non linear time domain simulation, which include proper modeling.

Large disturbance voltage stability, as discussed in section 1.2.1, may be further subdivided in to transient and long term time frames.

Small-disturbance (or small signal) voltage stability is concerned with a system's ability to control voltages following small perturbations, such as gradual change in loading. This form of voltage stability can be effectively studied with steady-state approaches that use linearization of the system dynamic equations at a given operating point.

Following a disturbance, the system voltages often do not return to the original level. Therefore, it is necessary to define the region of voltage level considered acceptable. The system is then said to have finite stability within the specified region of voltage level.

1.3.2 Analysis of voltage stability

The analysis of voltage stability for a given system state involves the examination of two aspects

1) *Proximity to voltage instability*: how close is the system to voltage instability? Distance to instability may be measured in terms of the physical quantities, such as load level, active power flow through a critical interface, and reactive power reserve. The most appropriate measure for any given situation depends on the specific system and the intended use of the margin; for example, planning versus operating decisions Consideration must be given to possible contingencies (line outages, loss of generating unit or a reactive power source, etc.)

2) *Mechanism of voltage instability*: How and why does instability occur? What are the key factors contributing to instability? What are the voltage- weak areas? What measures are most effective in improving voltage stability?

Dynamic analysis provides the most accurate replication of the time responses of the power system. Accurate determination of the time sequence of the different events leading to system voltage instability is essential for post-mortem analysis and the coordination of protection and control. However, time-domain simulations are time consuming in terms of CPU and engineering required for analysis of results. Also, dynamic analysis does not readily provide information regarding the sensitivity or degree of instability. These may make dynamic analysis impractical for examination of a wide range of system conditions or for determining stability limits unless combined with other techniques. Development and commercialization of new computer programs are constantly addressing and relieving these limitations. Commercially available software with combined time-domain and other (e.g., eigen value analysis) techniques, as well as advanced time simulation techniques (e.g., those with variable step size) overcome these limitations.

System dynamics influencing voltage stability are usually slow. Therefore, many aspects of the problem can be effectively analyzed by using static methods, which examine the viability of the equilibrium point represented by a specified operating condition of the power system. The static analysis techniques allow examination of a wide range of system conditions and, if appropriately used, can provide much insight into the nature of the problem and identify the key contributing factors. Dynamic analysis, on the other hand, is useful for detailed study of specific voltage collapse situations, coordination of protection and controls, and testing of remedial measures. Dynamic simulations also examine whether and how the steady-state equilibrium point will be reached.

1.3.3 Dynamic analysis

The general structure of the system model for voltage stability analysis is similar to the transient stability analysis. The overall system equation, comprising a set of first order differential equation, may be expressed in the following general form

$$\dot{X} = f(X, V) \quad \ldots 1.1$$

and a set of algebraic equations

$$I(X, V) = Y_N V \quad \ldots 1.2$$

With the set of know initial conditions (X_0 ,V_0), where,

X= State vector of the system

V= Bus voltage vector

I = Current injection vector

Y_N=Network node admittance vector

Equations 1.1 and 1.2 can be solved in time-domain by using any of the numerical integration methods. The study period is typically on the order of several minutes. With the inclusion of special models representing the "slow system dynamics" leading to voltage collapse, the stiffness of the system differential equations is significantly higher than that of transient stability models. Implicit integration methods are ideally suited for such applications.

1.4 Modeling Requirement

Traditional analytical tools, including power flow and transient stability programs may not be particularly well suited to the analysis of all voltage stability problems. Longer term (also variously called long-term, mid-term and extended-term) dynamic simulations, in particular, require good models of the slow dynamics associated with voltage collapse. Better component model give utility engineers the ability to conduct detailed studies that more realistically reflect the behavior of power systems. This requires the modeling of important slow acting controls and protective devices.

Traditionally used transient stability programs ordinarily include dynamic models of the synchronous machines with their excitation systems, power system stabilizers (PSS), turbines and governors, as well as other dynamic models, such as loads, High Voltage Direct Current (HVDC) transmission, Static VAR Compensators

(SVC) and other fast acting devices. These component models and the accompanying solution algorithm are suitable for analysis of phenomena from tens of milliseconds (e.g., machine subtransient dynamics) up to several seconds or tens of seconds. The time frame of voltage collapse can be as much as two orders of magnitude longer than either the component models or the solution algorithm of a transient stability program are designed to handle. Furthermore, it is well known that slower acting devices, such as load-tap-change (LTC) transformers, generator over excitation limits (OXL), and the characteristics of the system loads will contribute to the evolution of a voltage collapse. In a power flow program, these effects are taken into account, if at all, by enforcement of their steady-state (algebraic) response. Conversely, the transient stability program will typically assume that these phenomena are slow, and corresponding variables will remain constant. In actual practice, neither of these assumptions can always be relied upon, thereby requiring analysis of long term dynamic phenomena. The use of these techniques, including the effects of slow acting devices, allows utility engineers to develop a better understanding of the true limits of their systems. The impact of these devices on voltage stability is discussed below.

Ideally, the entire interconnected system including both the internal and external systems should be represented in as much detail as possible. In reality, however, some form of system reduction may be necessary to keep the size of the system manageable. However, more detailed representation of the distribution network of the internal system is required for accurate determination of voltage stability limits.

Most components of power systems can be modeled quite accurately, assuming sufficient resources are available to derive and/or identify model parameters. However, loads present a difficulty in modeling. Loads are a complex, time-varying mix of many different devices. It is therefore not sensible, and probably not even possible, to model every customer device connected to realistic power systems. Further, depending on the voltage level at which loads are defined, they may also contain several levels of load tap changer (LTC) transformers, switched capacitors, and load controls such as undervoltage load shedding. Certainly large individual, predictable loads such as aluminum smelters, or some motor loads, should be accurately modeled. But in general, generic aggregate load models must be used. For angle stability studies, aggregate load models have typically (though dubiously)

represented load powers as simple functions of voltage, i.e., without any form of dynamic response. As an example, loads were historically modeled as constant admittances. More recently they have been modeled as combinations of constant impedance, constant current and constant power (ZIP model), or in a voltage exponent form, e.g., $P(V) = P_o V^{\alpha}$, where α is a parameter chosen to best represent the voltage dependence of the aggregate load. However, these static models ignore the dynamic behavior exhibited by many loads. In voltage stability studies, this dynamic behavior is of importance.

Measurement in the laboratory and on the power system buses shows that a typical load response to a step change in voltage V is of the form shown in the fig 1.2 for real power demand P_d.

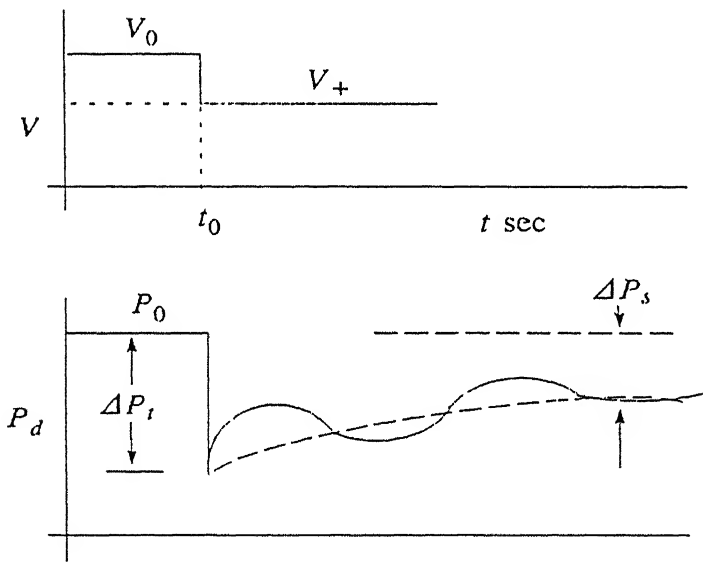

Figure 1.2 A typical load response

The response for real power and reactive power are qualitatively similar. The significant features are as follow,

- The step change in voltage V causes a step change in power demand P_d.
- Following this, the power demand recovers to a steady state value.

Intuitively, this behavior can be interpreted as follows. During the voltage step change, the induction motor slip can not change instantaneously, so the aggregate load

appears static. Thus, a step change of voltage produces a step change of power demand. On the longer time scale, the lower voltage tap changers and other control devices act to restore voltage and so the load. In fact the aggregate effect of distribution level restoration can be to cause load over shoot.

Confirmation of the above behavior can be found in laboratory test and measurement on the real system buses [9]. With the recovery time T_p on the time scale of few seconds, this behavior captures the behavior of induction machine. On the time scale of minute, the role of tap changers and other control devices is included. Over hours, the load recovery and possible overshoot may emanate from heating load. The following specific load types provide examples of this form of response.

Induction motor: When the voltage on an induction motor undergoes a step decrease, the induction motor load will immediately drop. This occurs because the machine slip cannot change instantaneously. However, this creates a mismatch between electrical and mechanical power which forces a restoring change in the slip. The load, therefore, quickly recovers.

Implicit LTC: As mentioned above, a load may include several levels of "downstream" LTC transformers. These transformers act to restore load bus voltages, and so lead to a recovery of voltage dependent loads. Therefore, when voltage steps down, voltage dependent loads and regulated bus voltages fall. LTC transformers then act to restore the load bus voltages and hence the loads.

Heating load: Thermostat controlled resistance devices, such as those used for space heating, exhibit long term recovery behavior. When voltage falls, the load resistance initially remains unchanged. Therefore the load power drops. Over time, this reduced electrical heating results in a fall in temperature. Individual thermostats compensate by increasing the on-time of their resistance. Therefore, the aggregate load resistance reduces (more devices on) and the aggregate load demand increases. The load will recover to a steady state in which the heater input is equal to the energy being lost to the surrounding environment or in which the load recovery is limited by all the heater being on continuously.

1.5 Tools and Techniques

Traditionally, power system engineers have used two main classes of programs for analysis of bulk power system performance:

(1) Power flow, and
(2) Transient stability.

Historically, voltage, active power and reactive power flow problems have been analyzed using static power flow programs. This approach was satisfactory, since these problems have been governed by essentially static or time-independent factors. Static analysis involves only the solution of algebraic equations and, therefore, is computationally much more efficient than dynamic analysis. Static analysis is ideal for the bulk of studies in which voltage stability limits for many pre-contingency and post-contingency cases must be determined.

Dynamic issues, such as first swing transient stability problems, have normally been addressed using a transient stability program. These programs ordinarily include dynamic models of the synchronous machines with their excitation systems, power system stabilizers (PSS), turbines and governors, as well as other dynamic models, such as loads, High Voltage Direct Current (HVDC) transmission, Static Var Compensators (SVC) and other fast acting devices. These component models and the accompanying solution algorithm are suitable for analysis of phenomena from tens of milliseconds (e.g., machine subtransient dynamics) up to several seconds or tens of seconds.

Dynamic analysis provides the most accurate replication of the time responses of the power system. Accurate determination of the time sequence of the different events leading to system voltage instability is essential for post-mortem analysis and the coordination of protection and control. However, time-domain simulations are time consuming in terms of CPU and engineering required for analysis of results. Also, dynamic analysis does not readily provide information regarding the sensitivity or degree of instability. These may make dynamic analysis impractical for examination of a wide range of system conditions or for determining stability limits unless combined with other techniques.

With the evolution of modern, heavily compensated power systems, voltage stability has emerged as the limiting consideration in many systems. The phenomenon of voltage collapse is dynamic, yet frequently evolves very slowly, from the perspective of a transient stability program. For example, the 1987 collapse of the Tokyo Electric Power Company system evolved over a period of about 30 minutes (1800 seconds). The time frame of such an event is roughly two orders of magnitude longer than either the component models or the solution algorithm of a transient stability program are designed to handle.

It is well known that slower acting devices, such as under load tap-change (ULTC) transformers, generator over excitation limiters (OXL), and the characteristics of the system loads will contribute to the evolution of a voltage collapse. In a power flow program, these effects are taken into account, if at all, by enforcement of their steady-state (algebraic) response. Conversely, the transient stability program will typically assume that these phenomena are slow, and corresponding variables will remain constant. In actual practice, neither of these assumptions can be relied upon, thus leaving voltage collapse in a no-mans-land between these two analytical domains.

The recent emergence of a new class of computer simulation software provides utility engineers with powerful new tools for analysis of long term dynamic phenomena. The ability to perform long-term dynamic simulations either with detailed dynamic modeling or simplified quasi-steady-state modeling permits more accurate assessment of critical power system problems than is possible with conventional power flow and transient stability programs.

1.5.1 Power flow analysis

In the past, electric utilities largely depended on conventional power flow program for static analysis of voltage stability. Voltage stability is determined by computing the P-V and Q-V curves at selected buses. Generally, such curves are generated by executing a large number of power flows using conventional models. The stability characteristics are established by stressing each bus independently. This may unrealistically distort the stability condition of the system. Also, the buses selected for the V-P and Q-V analysis must be chosen carefully and large number of such curve are required to obtain complete information.

Power flow programs are constrained by a set of modeling assumptions, which are valid for a wide range of system problems. These constraints are,

1. Fixed real power dispatch of generators with a swing bus to handle the slack power.
2. Constant P-Q loads (no voltage or frequency sensitivity).
3. Instantaneous LTC action.
4. Fixed or instantaneously switched capacitors and reactors.
5. Generator limits represented as maximum and minimum reactive power limits.
6. Perfect voltage control at PV buses.

The algorithms typically used for solution of the power flow equations also have some limitations. The most common solution technique is some type of Newton iteration on the power equations. The most notable limitation of these algorithms is that the Newton iterations tend to become ill-conditioned, and ultimately non-convergent, as the system nears the point of voltage collapse. This is primarily because the Jacobian of the network equations approaches singularity.

1.5.2 Transient and long term dynamic analysis

It may be worth examining a case taken from ref. [16] for which the transient performance would normally have been the starting point for analysis.

In this case, a relatively tightly interconnected 500 kV test system [16] which has been described in chapter 2 & 3, is initially stressed with a heavy level of transfer from the generation rich region towards an area with both heavy loads and a considerable amount of local generation.

The disturbance considered is the loss of one of the lines between generation rich region and load region. Figure 1.3 shows the transient response of this system. As the figure shows, the system is transiently stable, with system oscillations showing relatively good damping. The response of the system in the described above, appears to result in a satisfactory post disturbance condition. However, if we continue the case in a longer term simulation, the response of the system becomes rather alarming. (see figure 1.4).

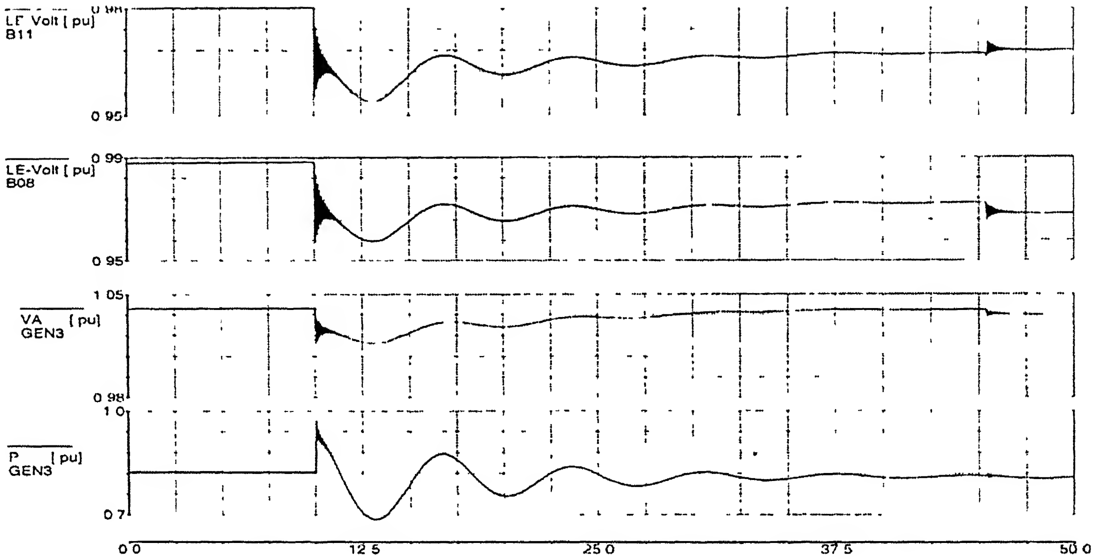

Figure 1.3 Transient response of a system [16]

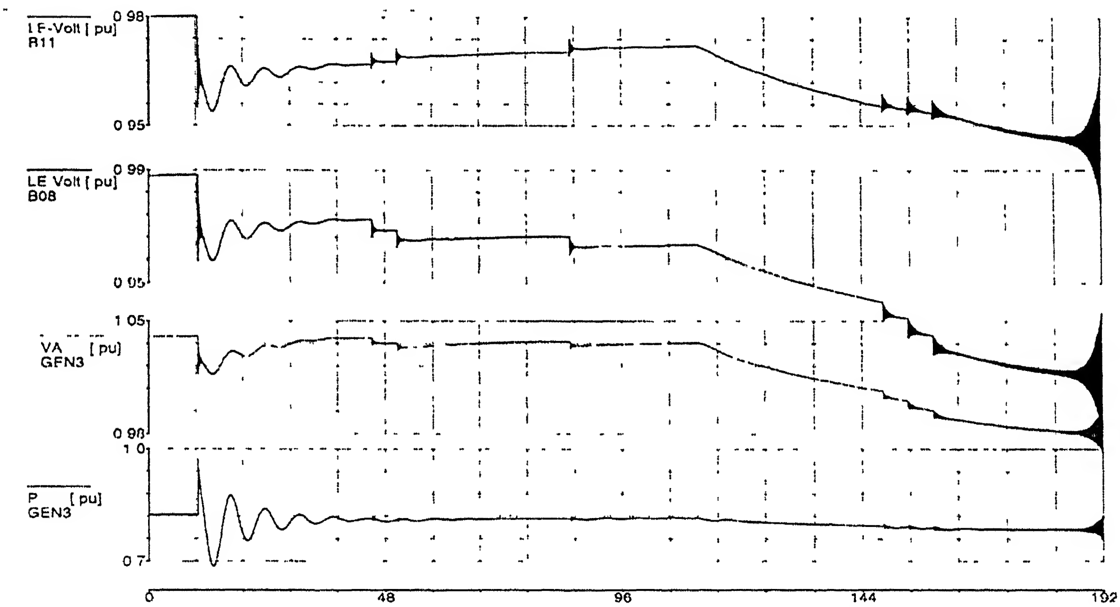

Figure 1.4 Long term response of the system [16]

Simulation of the system for more than about ten seconds requires consideration of a number of longer term dynamic phenomena such as loads, LTCs. In addition, it is also important to consider the response of power plant controls, boiler dynamics, and the automatic generation control (AGC).

Here, in this case, one can see that after about 120 sec, over excitation limiter of the generator operate and it starts ramping down the field current of the generator 3 to its lower value. Due to that the terminal voltage of generator 3 start falling and after some time system collapses.

1.6 State-of-the-Art

The concept of voltage stability is not so recent [5]. It dates back to the first half of the century. However, due to non-availability of proper protective devices, SVCs and generator fast speed governing systems, transient stability was the main concern for the researchers. In the last two decades, the problem of voltage stability has largely attracted the attention of researchers due to several incidents of voltage collapse observed in different countries and due to stressed nature of power system in general.

Number of papers exist in the area of voltage stability and it is difficult to present a detailed review of all of them. Hence, only a representative survey of literature, relevant to the work carried out in the thesis, is presented below.

Initially, voltage stability investigations have been based on steady state analysis, using power flow model [5-6]. The realization that voltage stability is a dynamic phenomenon has led to the application of the time simulation based dynamic approach. This is evident from the recent research trends [6-16] to also consider the effect of system dynamics for study of voltage collapse phenomenon. System dynamics include the generating unit dynamics including mechanical dynamics & exciter dynamics and network dynamics such as tap changer & load dynamics. Taylor et al [14] explained the concept of dynamic analysis of voltage instability. Kundur et al [1] extended the concept by considering dynamics of load tap changer & overexcitation limiter of generator and also with the consideration of various load models. Gurga prasad et al [8] and also A Gebreselassie et al [7] have done voltage stability analysis using eigen value approach on the New England Test bus system.

Voltage instabilities are mostly related to heavily stressed systems and results in load bus voltage collapse, The load dynamics is considered to be the key to understanding the mechanism of voltage instability. There have been number of papers presented for the load modeling in the power system. IEEE task force on load representation for the dynamic performance is working on the load modeling. A paper by IEEE task force on load representation for the dynamic performance [16] highlights the importance of load modeling in power system simulation studies. The paper describes different approaches and modeling practices used by electrical utilities. In particular, the paper describes several alternative model structures. No recommendation, however, is made regarding standard models for industry use.

Another paper [17] by the same committee suggests the standard load models for power flow and dynamic simulation programs. Walve et al [22] shows the extent of load model details that the Swedish State Power Board had to use to duplicate the field record of the 1983 blackout. Initial efforts using simple static load models failed to explain the voltage collapse scenario.

Hill et al [7] have proposed the generic dynamic load model intended to capture the usual nonlinear steady-state behavior plus load recovery and overshoot. Xu et al [6] also proposed similar kind of load model for the voltage stability analysis. Karlson et al [5] have proposed load model based on the measurement based approach.

1.7 Motivation

From the literature survey, it is found that most of the work on voltage stability analysis have been done using the static model of the power system and very few analysis have used dynamic tool.

Dynamic analysis provides the most accurate replication of the time response of the power system and loads. The loads are voltage dependent and this becomes the critical aspect of the voltage stability analysis. Further, it was shown in section 1.5.2 that although system may appear to be stable through transient simulations, it may become unstable due to action of the slow acting devices in a long term dynamic simulation. Hence the motivation behind the present work was,

- To perform long term dynamic simulation for the voltage stability analysis.
- To show the effect of slower acting devices , such as transformer load tap changer (LTC) transformer & generator over excitation limiters (OXL)
- To study the effect of various static & dynamic load models and different load levels on the voltage instability and voltage collapse.

1.8 Thesis Organization

The present thesis has been organized in four chapters.

The present *Chapter 1* introduces voltage instability problem, presents some of the basic concepts, tools & techniques along with a brief state-of-the-art and sets the motivation behind the work reported in this thesis.

Chapter 2 first presents the various static and dynamic load models. Long term dynamic simulation results on 11 bus test system are presented for the different load models

Chapter 3 presents the impact of generator overexcitation limiter(OXL), under load tap changer (ULTC) and different load levels on voltage instability and collapse on the two test systems including 11-bus system and the 39-bus New England system.

Chapter 4 concludes the main finding of the thesis and suggests some future scope of the work.

CHAPTER 2

LOAD MODELING FOR VOLTAGE STABILITY STUDIES

2.1 Introduction

Stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical loads in the system. Consequently, load characteristics have an important influence on system stability.

The modeling of loads is complicated because a typical load bus represented in stability studies is composed of a large number of devices such as fluorescent and incandescent lamps, refrigerators, heaters, compressors, motors, furnaces, and so on. The exact composition of load is difficult to estimate. Also, the composition changes depending on many factors including time (hour, day, season), weather conditions, and state of the economy.

Even if the load composition were known exactly, it would be impractical to represent each individual component as there are usually millions of such components in the total load supplied by a power system. Therefore, load representation in system studies is based on a considerable amount of simplification.

In this chapter some of the static and dynamic load models relevant to the voltage stability studies have been discussed. Their effect on voltage stability has been demonstrated on a 11-bus test system.

2.2 Load Modeling

Various static and dynamic load models, focusing on the properties of widely used static exponential & polynomial load models and a generic dynamic load models are discussed below.

2.2.1 Static load model

A static load model expresses the characteristic of the load at any instant of time as algebraic function of the bus voltage magnitude and frequency at that instant. The active power component P and the reactive power component Q are considered separately.

(a) Exponential load model

Traditionally, the voltage dependency of load characteristics has been represented by the exponential load model, which has the general form

$$P = P_0 V_p^{\alpha}$$

$$Q = Q_0 V_p^{\beta}$$

Where, $V_p = V/V_0$, P and Q are active and reactive component of the load when the bus voltage magnitude is V. The subscript '*o*' identifies the values of the respective variables at the initial operating condition

The parameters of this model are the exponents α and β. With these exponents equal to 0, 1, or 2, the model represents constant power, constant current, or constant impedance characteristics, respectively. For composite loads, their values depend on the aggregate characteristics of load components.

The exponent α *(or* β) is nearly equal to the slope *dPldV (or dQldP) at V=Vo.* For composite system loads, the exponent α usually ranges between 0.5 and 1.8; the exponent β is typically between 1.5 and 6 [1]. A significant characteristic of the exponent β is that it varies as a nonlinear function of voltage. This is caused by the magnetic saturation in distribution transformers and motors. At higher voltages, Q tends to be significantly higher.

(b) Polynomial load model

An alternative load model, which has been widely used to represent the voltage dependency of the load, is the polynomial load model

$$P = P_0[p_1(\frac{V}{V_0})^2 + p_2(\frac{V}{V_0}) + p_3] \qquad \ldots 2.1$$

$$Q = Q_0[q_1(\frac{V}{V_0})^2 + q_2(\frac{V}{V_0}) + q_3] \qquad \ldots 2.2$$

Where,

V_0 is initial voltage on the node, which may be approximately rated voltage;

P_0 and Q_0 are initial load power;

p_1, p_2, p_3 are, respectively, percentage of active load of constant impedance, constant current and constant power;

q_1, q_2, q_3 are respectively percentage of active load of constant impedance, constant current and constant power;

This model is commonly referred to as the ZIP model, as it is composed of constant impedance (Z), constant current (I), and constant power (P) components . The parameters of the model are the coefficients p_1 to p_3 and q_1 to q_3, which define the proportion of each component.

The frequency dependency of load characteristics is usually represented by multiplying the exponential model or the polynomial model by a factor as follows

$$P = P_0[p_1(\frac{V}{V_0})^2 + p_2(\frac{V}{V_0}) + p_3](1 + K_{pf}\Delta f) \qquad \ldots 2.3$$

$$Q = Q_0[q_1(\frac{V}{V_0})^2 + q_2(\frac{V}{V_0}) + q_3](1 + K_{qf}\Delta f) \qquad \ldots 2.4$$

Where, Δf is the deviation of actual frequency from rated frequency $\Delta f = f - f_0$,K_{pf},is the slope of active power load frequency static characteristic at steady state operating point. Typically , K_{pf} ranges from 0 to 3.0. K_{qf} is the slope of reactive power load

frequency static characteristic at Steady State operating point. Typically , K_{qf} ranges from –2.0 to 0.0.

2.2.1 Dynamical load model

The fact that loads are generally voltage dependent is a critical aspect of voltage stability analysis. The voltage sensitivity of the loads can provide some system relief following a voltage depression. However, some types of loads, particularly heating loads, exhibit a thermostatic effect. Here, the reduced power consumption of the individual loads results in the thermostats leaving the loads 'ON' for longer period. The aggregate effect of this is to gradually push the consumed load back towards the pre-disturbance level. Thus, the actions of the LTCs and the thermostatic effects of the loads will cause any load relief to be short-lived. Other loads, such as air conditioners, have characteristics that tend to maintain their active power consumption and actually increase their reactive demand as the voltage drops. Failure to model the voltage dependence and thermostatic effects of the loads can lead to erroneous conclusions about the state of the system and the control actions required following a contingency.

For purposes of system studies, the term "load" refers to the equivalent representation of the aggregate effect of many individual load devices and the interconnecting distribution and subtransmission systems that are not explicitly represented in the system model. Generally, the load is represented by some combination of static and dynamic models to approximate the voltage (and frequency) sensitivity of the aggregate load. The effect of the series impedance of feeders and transformers between the system bus and the loads is usually neglected or included as a lumped impedance and tap ratio.

The representation of loads for voltage stability analysis involves several aspects not required for conventional stability analyses, including: longer-term dynamics due to thermostatically-controlled loads and due to voltage regulating devices; and nonlinearities in the voltage characteristics at low voltages (e.g., due to motor stalling and tripping, discharge lighting, and inverter or switching power supplies).The modeling of these effects is not well-established and is still the subject of ongoing investigation.

pre-disturbance level, the voltage dependence, as viewed from the bulk system, is eliminated. While the system voltage may have changed significantly, the voltage seen by the load has returned to its pre-disturbance state. Therefore, the power consumed, regardless of the load voltage dependence, is relatively constant.

Following bulk system upsets, a typical result is an immediate drop in the power consumption and the system voltages. Over the next few minutes, the action of voltage control devices will typically drive the system into conditions of still lower voltage and possibly collapse. Sometimes, when a system settles down to a condition of steadily declining voltages on the bulk system, it is due to the fact that while most of the voltage control devices have run out of regulating range, the thermostatic effects continue to push the voltage down, possibly into voltage collapse.

If cases such as these are run on a power flow using constant power load modeling, the post-contingency power flow would simply fail to converge. In a conventional power flow, the finite range of the voltage regulating devices between the transmission system and the loads is ignored. This is reflected in the constant power load model connected at transmission buses. The effect of this modeling is to cause the voltage to cascade downward, without hitting the limit imposed by the maximum tap range of the LTCs. These effects can be included either within the load model, or by explicit modeling of the voltage control devices in the analysis. Dynamic simulation also permits consideration of the timing of voltage control actions, wherein some devices will act before others, thereby changing the course of the scenario. Explicit modeling of these devices is discussed further below.

(c) Induction Motors

The characteristics of induction motors at low terminal voltages should be properly modeled. For dynamic voltage stability studies, a simplified first order model with slip being the only state variable may be adequate. Dynamic forms of load models are discussed next.

2.2.1.1 Generic dynamic load model

In section 1.5.2 a typical response of an aggregate load to step voltage changes is already shown. The response is a reflection of the collective effects of all down stream component ranging from LTCs to the individual household loads. The time

span for the load to recover to steady state is normally in the range of several seconds to minute depending on the load composition. Response for the real and reactive powers are qualitatively similar. It can be seen that sudden voltage change causes an instantaneous power demand change. This change defines the transient characteristic of the load. When the load response reaches steady state, the steady state power demand is a function of the steady state voltage.

The typical load voltage response characteristic can be modeled by a generic dynamic load model [11]. This model can be expressed mathematically in the state space form for the real power as

$$\dot{X}_p = -X_p / T_p + P_s(V) - P_t(V) = P_s(V) - P_d \qquad \ldots 2.5$$

$$P_d = X_p / T_p + P_t(V) \qquad \ldots 2.6$$

X_p is an internal state , P_d is the power demand, and T_p is the time constant which describe the rate of recovery of the load.

When the voltage undergoes a step change, the internal state cannot change instantaneously. However, the algebraic "output" equation shows that P_d will vary according to the function $P_t(V)$. Over time X_p will respond, driven by the differential equation. Steady state will be reached when $P_d = P_s(V)$. Therefore, the initial transient step change in load, the final value of load, and the recovery rate are described by $P_t(V)$, $P_s(V)$ and T_p respectively. To match this model to an actual load response, parameter T_p and the parameters of $P_t(V)$ and $P_s(V)$ would need to be identified.

The exponential recovery load model has been illustrated for real power load. A similar set of equations could be used to model reactive power. Alternatively, and more realistically, some coupling between the real and reactive loads should be incorporated into the model. More general forms of the load model are discussed later. The recovery load model given above in state space form can also be expressed in input-output form. The input-output form of the model is shown in figure 2.1, where the input is voltage V and the output is the power demand P_d . This block diagram form illustrates the interaction between nonlinear functions and a linear transfer function. For the exponential recovery model, the linear transfer function is

first order. However, higher order dynamic behavior, such as oscillatory recovery, can be modeled by a higher order transfer function involving multiple time constants.

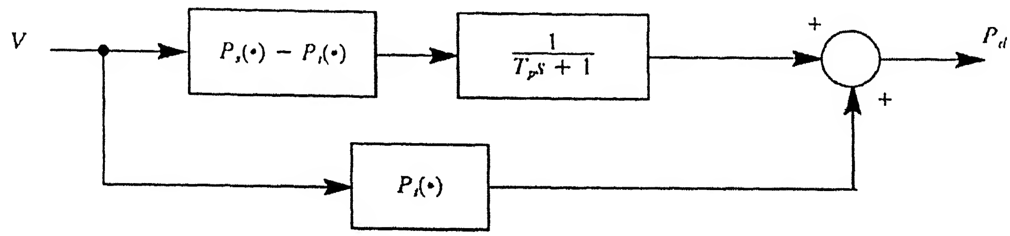

Figure 2.1 Input Output form of the load model

The exponential recovery load model [11] is one example of a model, which captures dynamic behavior of loads. Many other models exist. Typically, they fit in to the general form given below

$$\dot{X} = a(X; V) \quad \ldots 2.7$$

$$P_d = b_p(X; V) \quad \ldots 2.8$$

$$Q_d = b_q(X; V) \quad \ldots 2.9$$

where , X may be a vector. The various load models correspond to different functions a, b_p and b_q , and different dimensions for X.

Several recent references [9-15] have proposed simplified dynamic load models intended to capture the essential behavior of loads with different transient and steady-state characteristics, such as thermostatically-controlled loads and (with considerable care) some motor-driven loads. Figure 2.2 shows the generic load model in block diagram form. The difference between the model proposed and that in [10] is that the final summation is replaced by a multiplication.

In this model, the steady-state load-voltage characteristic is represented by the function g(V), which may be an exponential or polynomial in V. For a thermostatic load, this would normally be represented as constant power. The transient characteristic is represented by the function f(V), which will often be constant impedance. Frequency sensitivity can also be included in both of these functions.

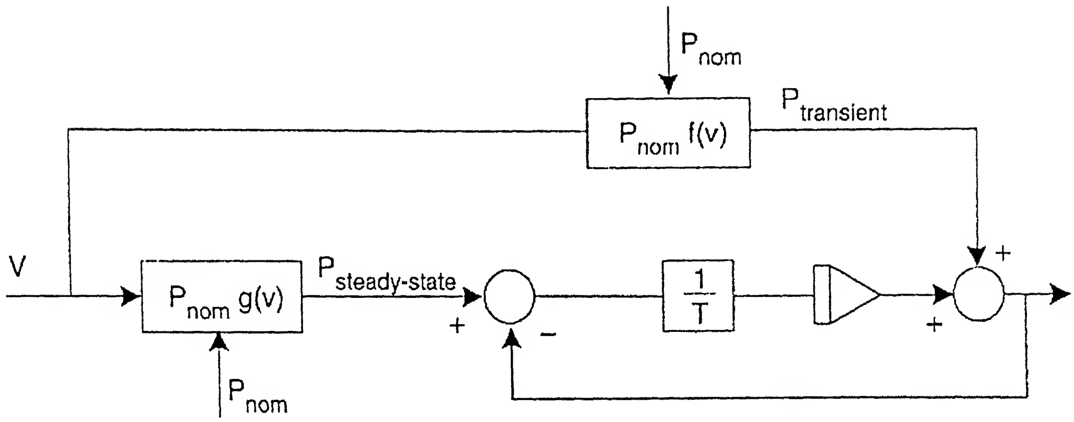

Figure 2.2 Simplified Dynamic load model

Function g(v) and f(v) can be expressed as

$$P_t = V^{\alpha} \quad or \quad P_t = A_2 V^2 + A_1 V + A_0 \qquad ...2.10$$

$$P_s = P_o V^{a} \quad or \quad P_s = P_0 (B_2 V^2 + B_1 V + B_0) \qquad ...2.11$$

Where, V is the per unit magnitude of the voltage imposed on the load.

Similarly, for the reactive power

$$Q_t = V^{\beta} \qquad ...2.12$$

$$Q_s = P_o V^{b} \qquad ...2.13$$

The language used to describe loads, when including voltage and frequency considerations is not well standardized. Recent IEEE and CIGRE documents have suggested the use of *nominal load power* as the amount of MW the load would consume at nominal conditions, i.e., 1.0 p.u. voltage and frequency. This is designated as P_{nom} in figure 2.2 (It is initially equal to the MW consumed by the load divided by g(V) for the initial voltage.) The *actual or consumed load power*, also measured in MW, is the power consumed by the load under the existing conditions of voltage and frequency, i.e., the power measured by a meter. For this type of analysis, it is of vital importance to recognize that the *nominal load* is the independent variable, and *not* the actual load power.

A general distinction between the power consumed by a particular load at nominal conditions and under other conditions is given by:

$$P = P_o f(V,w,t) \qquad ...2.14$$

and

$$Q = Q_o\, g(V,w,t) \qquad \ldots 2.15$$

where, by the definitions proposed by CIGRE,

P_o is the active component of the *nominal load*

Q_o is the reactive component of the *nominal load*

P is the active component of the *consumed load*

Q is the reactive component of the *consumed load*

This requires that the load voltage/frequency sensitivity functions, $f(V,w,t)$ and $g(V,w,t)$, be unity at nominal steady-state conditions:

$$f(V,w,t) = 1.0 \text{ at } V = 1.0 \text{ p.u., } w = 1.0 \text{ p.u., and } t \rightarrow \infty$$

$$g(V,w,t) = 1.0 \text{ at } V = 1.0 \text{ p.u., } w = 1.0 \text{ p.u., and } t \rightarrow \infty$$

To illustrate the behavior of this model, a simple radial system was simulated, with a load, represented by the model in figure 2.2, connected through a transformer and transmission line to an infinite bus. A constant-impedance transient characteristic was used, with a constant-power steady-state characteristic, and a transition time constant (T) of 1.0 seconds. (Actual values of T for heating loads are much longer – up to several hundred seconds according to reference [9].) Reactive power load was modeled as constant impedance type.

Figure 2.3 shows the response of this model (both with the summation and with the multiplication) to a 10% upward change in the high-side tap, followed 10 seconds later by a return to the original tap position. The response of the two forms of the model is similar. Because the load bus is not infinitely stiff, the bus voltage changes in response to the changing load power consumption.

Figure 2.4 illustrates the response of the dynamic load model to a 10% downward change in the *nominal load power*, followed after 10 seconds by a return to the initial value. There is an initial response due to the transient characteristic, which however is modified by a change in the bus voltage due to the finite system stiffness. In the steady state, the actual power matches the nominal power due to the constant power steady-state characteristic.

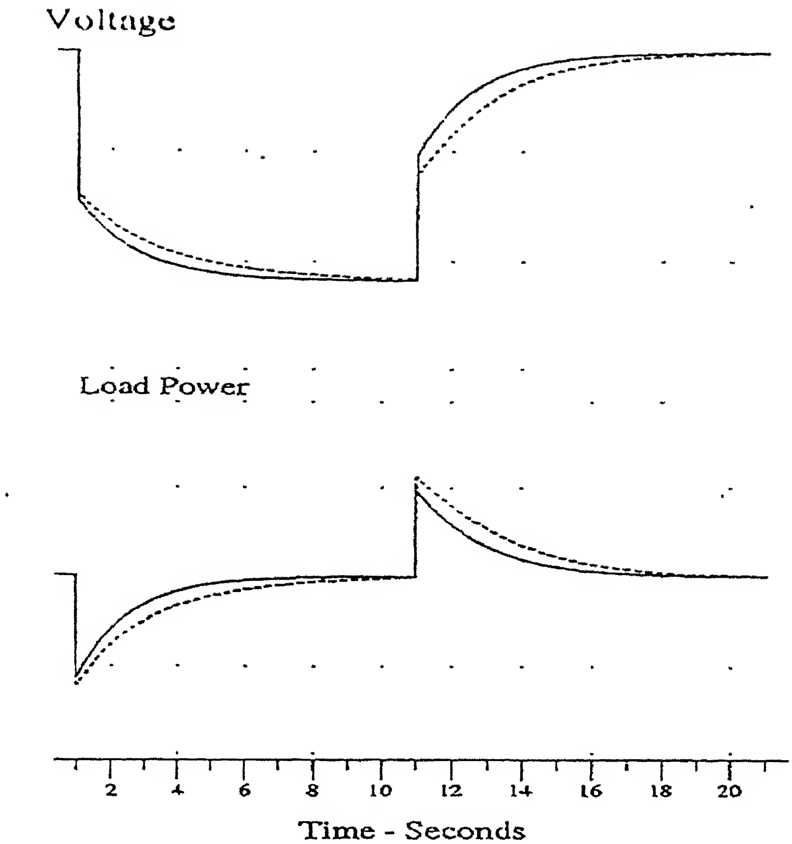

Figure 2.3 Dynamic Load Model Response to 10 % Tap Change (Solid Line-Summation form, Dotted- Multiplication form)

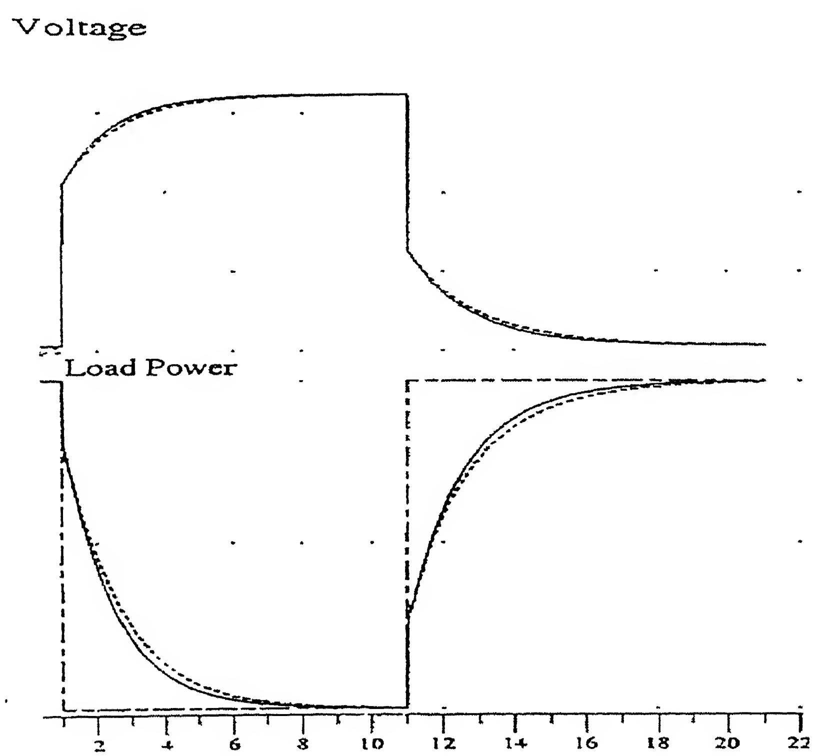

Figure 2.4 Dynamic Load Model Response to Change in P_{nom} (Solid line – summation form, Dotted-Multiplication form)

2.3 Determination of Load model Parameter

The best way to understand the meaning of the parameters in the generic dynamic load model is to visualize a typical (step voltage) load test in the V-P (or V-Q) plane (Figure 2.5). In this case, the system V-P curve is flat and the initial operating point (V_0, P_0) is the intersection of the V-P curve V_0 and the steady-state load characteristic $P_s(V)$.

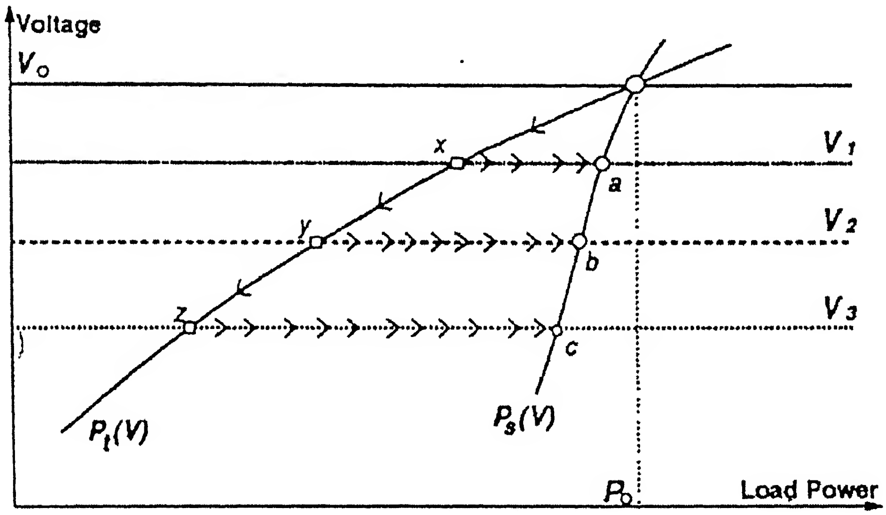

Figure 2.5 Load test as viewed from V-P plane

When the voltage is stepped down to V_1 the operating point jumps to *x*. Since a constant voltage is maintained at the reduced level, the operating point drifts horizontally to the steady-state point *a*. For different step voltage changes, there is a different pair of transient and steady-state operating points. These points are shown in Figure 2.5 as *(x, a), (y, b) and (z, c)*. Connecting points *x. y* and *z* gives the transient load characteristics and connecting *a, b* and *c* gives the steady-state load characteristics.

Any curve fitting technique can be used to calculate the steady-state load characteristic function $P_s(V)$. The determination of $P_t(V)$ needs more explanation because the state variable x is involved. For a given set of voltage step tests, the instant load demands after the voltage steps are:

$$P_1 = x\,P_t(V_1)$$

$$P_2 = x\,P_t(V_2)$$

$$\cdot \quad \cdot \quad \cdot$$

$$P_k = x\,P_t(V_k) \ldots \qquad \ldots 2.16$$

Where the state variable x has the pre-disturbance value defined by

$$P_0 = x\,P_t(V_0) \qquad \text{...2.17}$$

Dividing the equation in Eq. 2.16 by Eq 2.17 and considering that $P_1 = x\,P_t(V_1)$ has a form of V^{α}, we can get

$$P_1/P_0 = (V_1/V_0)^{\alpha}$$

$$P_2/P_0 = (V_2/V_0)^{\alpha}$$

$$\cdot \quad \cdot \quad \cdot$$

$$P_k/P_0 = (V_k/V_0)^{\alpha} \qquad \text{...2.18}$$

Parameter α can, then, be determined by curve fitting the above equations. The time constant T_p can be determined from any one of the load test curve as follows:

$$T_p = T_1 \frac{T_t(V_1)}{\mathit{IN}(P_a - P_x) - \mathit{IN}(0.1P_a)} \qquad \text{...2.19}$$

Where,	V_1	is the step down voltage
	P_a	is the steady state load demand at V_1
	P_x	is the transient load demand (P at point x)
	P_{at}	is the time span for the load to recover to 90 % of P_a

The reactive power dynamic parameters can be determined in exactly the same way as those of real power. Typical load parameters are α= 0.72 ~1.30, ß=2.96 ~ 4.38 for residential load; α= 0.99 ~1.51, ß=3.15 ~ 3.95, for commercial load; and α= 0.18, ß=6.0 for industrial load [24]. The steady-state load parameters and load time constant depend strongly on the voltage level at which the load is aggregated since the downstream LTCs play a very important role. According to ref.[10], no data has been fully documented and a=0, b=0 are commonly used. B.C. Hydro's recent tests on *unregulated* residential loads (25kV) showed that a =0.75α, b= ß and the time constant is roughly 3 minutes. BPA's load tests on *regulated* loads (69kV) suggest that a and b are close to zero and the time constant is approximately 25 seconds.

2.4 Case study

To study the impact of different load models, a 11-bus, 500 kV test system as described in Appendix-A was considered. This system, as shown in figure A.1, has 3 generators, 2 load buses (bus 08 & 11), 6 transformers and capacitor banks at three buses. The lines, transformers, generators and load data are given in Table A.1 to A.4. For the generators, type DC -1A excitation system was considered as shown in figure A.2. Only transformer T_6 is assumed to have ULTC having the parameter values given in Appendix-A. The long term dynamic simulations were carried out for load level-3 (3385 MW & 1090 Mvar load at bus 08 and 3500 MW & 1030 Mvar load at bus 11) using NETOMAC software developed by Siemens AG, Germany. The load at bus 11 was considered to be constant active and reactive power (CARP) type. Three cases were studied by representing load at bus 08 by following models.

1) Constant active and reactive power (CARP) model.
2) ZIP model.
3) Generic dynamic load model (GDLM).

Figures 2.9 , 2.10 , 2.11 shows the active and reactive power drawn by the loads at bus 08 and 11 for the CARP, ZIP and GDLM models, respectively. After an

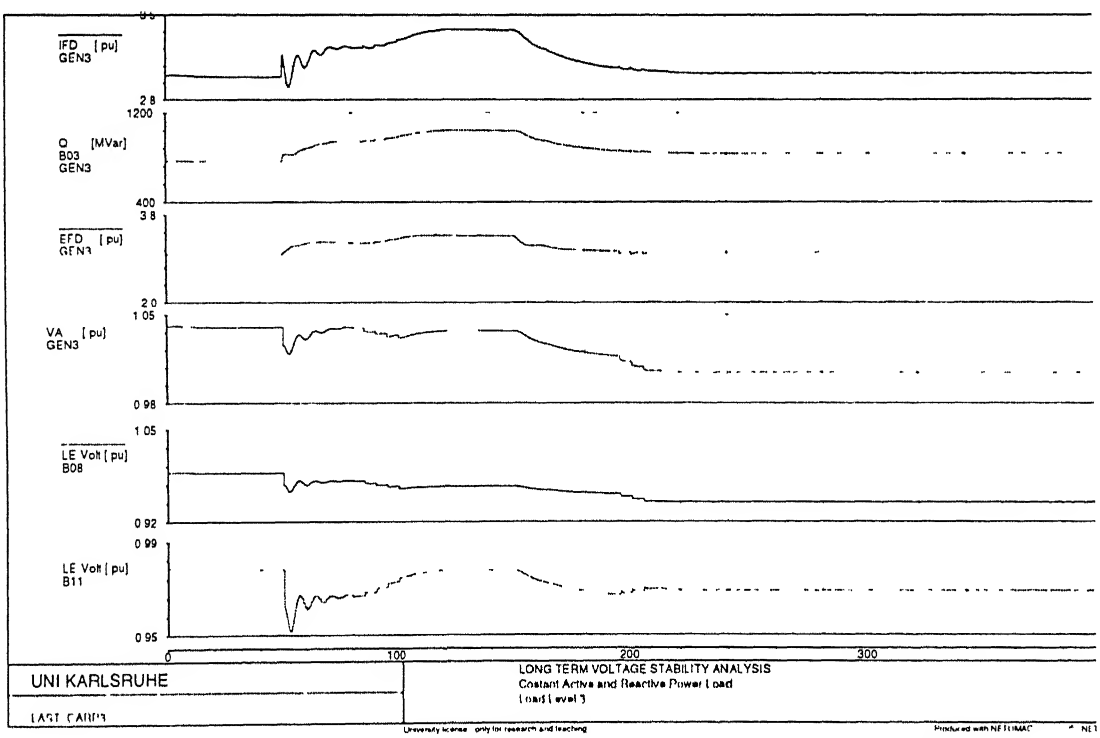

*Figure 2.6 Simulation results (Generator 3 exciter current, Q output, field voltage & terminal voltages and voltage at load buses) with **CARP load model** at bus 08*

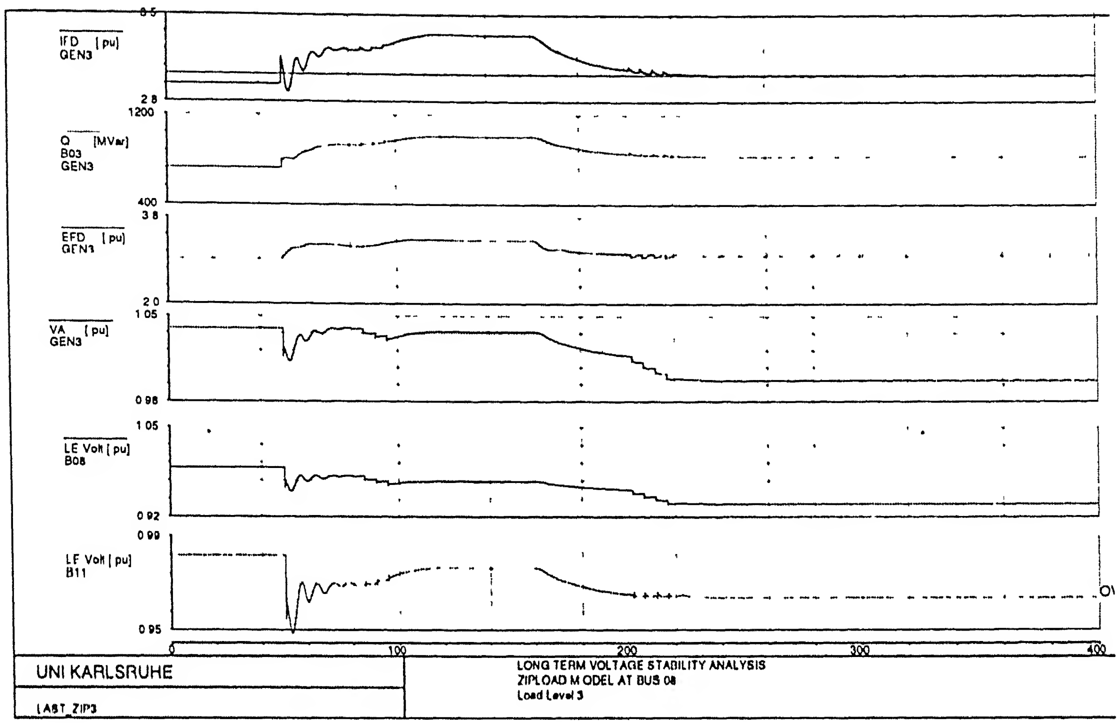

Figure 2.7 Simulation results (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load buses) with ***ZIP load model*** *at bus 08*

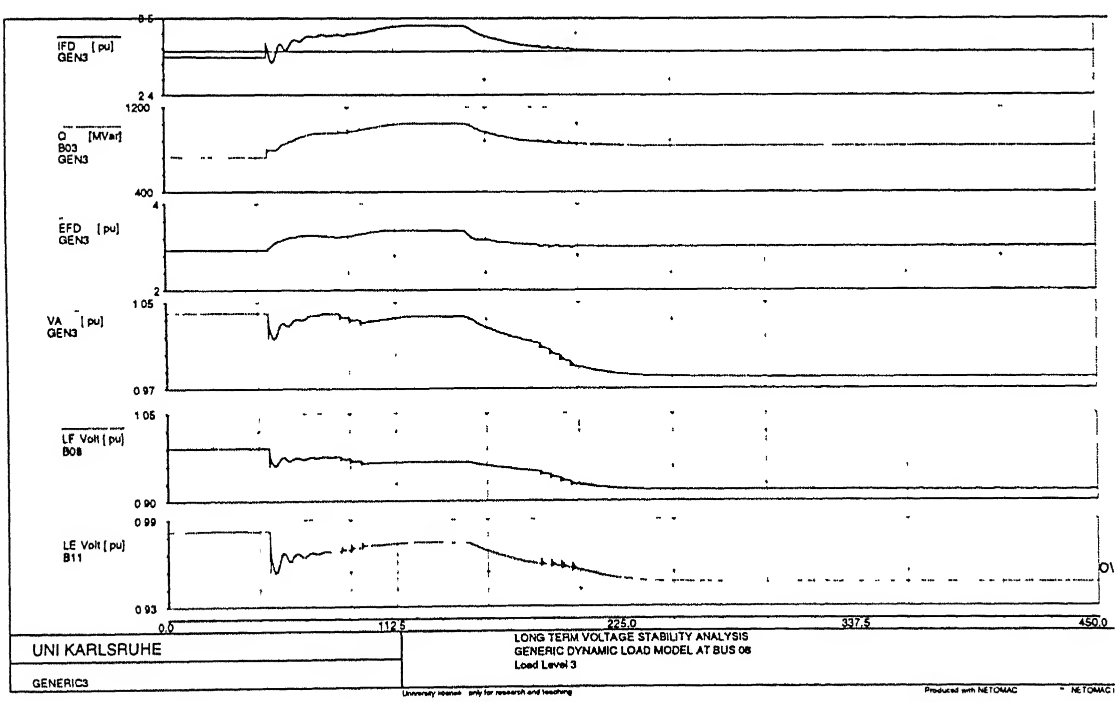

Figure 2.8 Simulation results (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load buses) with ***GDLM load model*** *at bus 08*

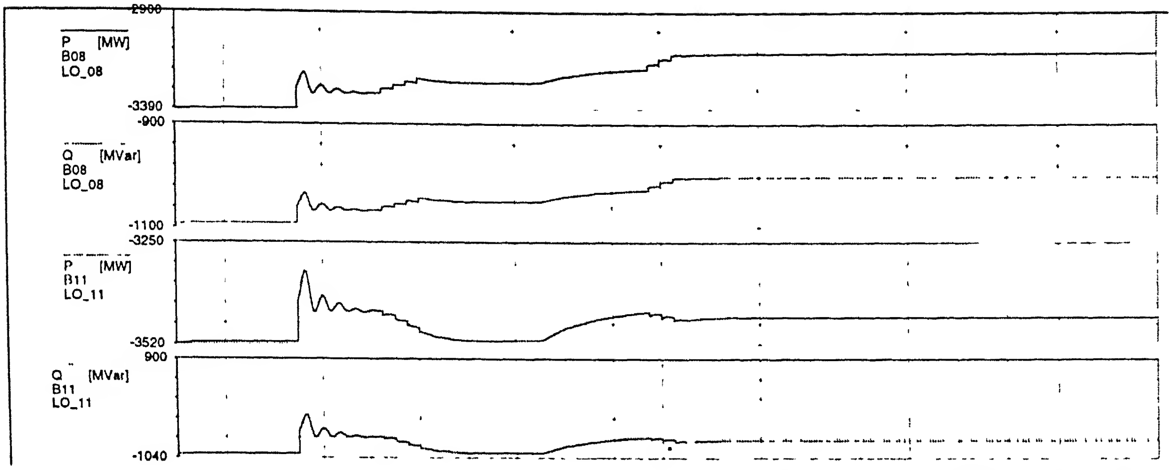

*Figure 2.9 Active and Reactive power load at load bus 08 and 11.**CARP load model** used at bus 08*

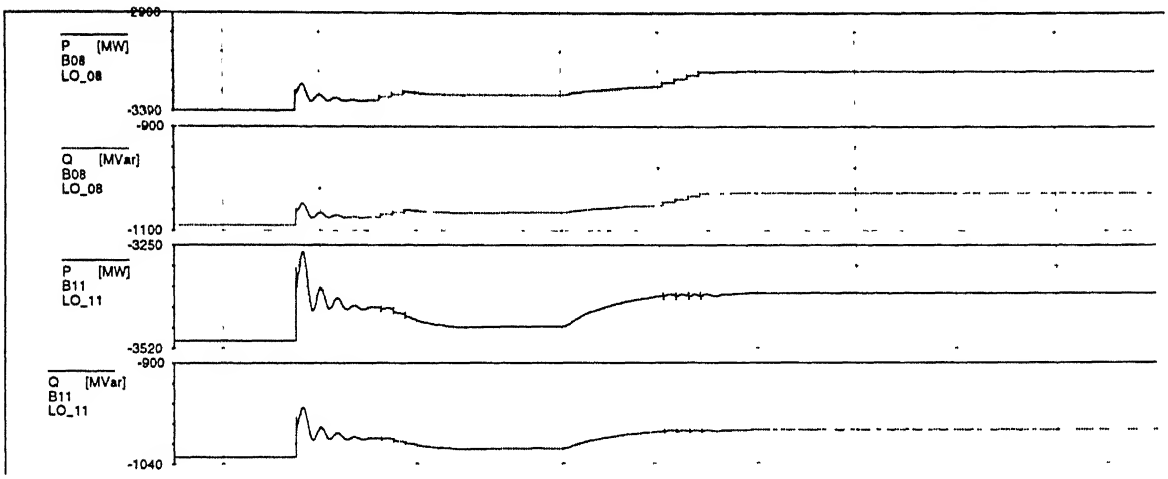

*Figure 2.10 Active and Reactive power load at load bus 08 and 11. **ZIP Load model** used at bus 08.*

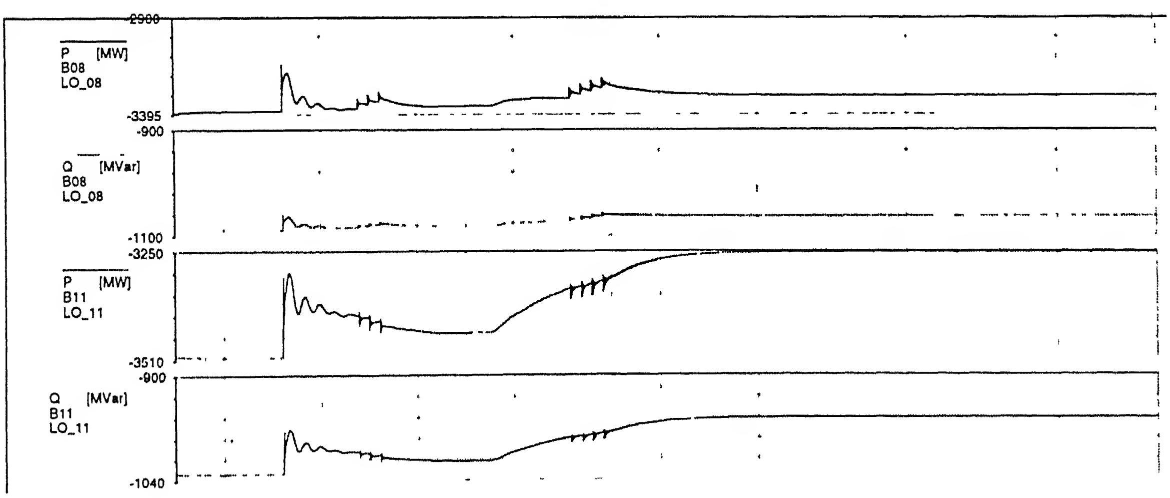

*Figure 2.11 Active and Reactive power load at load bus 08 and 11. **GDLM Load model** used at bus 08.*

outage of transmission line, active and reactive component of power in the case of GDLM recovers after some time and sets at a higher value compared to the CARP and ZIP load model.

Figure 2.6 , 2.7 and 2.8 shows the load bus voltages for the CARP, ZIP and GDML load models, respectively. In the case of GDLM, the power recovers after some time and due to that the voltages at load buses set at lower value compared to the constant power and ZIP Load model. Table 2.1 shows the comparison of the load bus voltages after all the dynamics die out

Table 2.1 Comparison of load bus voltages for different load model

Load Model	Voltages at		
	Bus 08	Bus 11	Gen. 3
Constant power load model(CARP)	0.948	0.968	1.002
ZIP load model	0.940	0.964	0.996
Generic dynamic load model(GDLM)	0.915	0.948	0.980

2.4 Conclusion

This chapter has reviewed various static and dynamic load models pertinent to the voltage stability studies. For studying the relative impact of load models on voltage stability, two static load models viz. constant active and reactive power (CARP), and a general ZIP load model, as well as generic dynamic load model (GDLM) was considered. The long term dynamic simulation results obtained on 11-bus test system reveal the followings.

1) Dynamic behavior of aggregate loads, which can be characterized by time constants, transient and steady state characteristics parameters, is the main factor determining the voltage collapse dynamics. The parameters of GDLM can be computed experimentally using the simple approach describe in the chapter.
2) In the case of a line outage, the active & reactive power componens of loads settel at relative higher value for GDLM as compared to the ZIP models and the CARP models in sequence.
3) After the line outage, the steady state load bus voltages recover to the lowest value considering the GDLM, followed by ZIP and the CARP load models.

CHAPTER 3

EFFECT OF OVER EXCIATION LIMITER AND TAP CHANGERS

3.1 Introduction

Dynamic simulation of power system for more than 20 seconds requires consideration of number of longer term dynamic phenomena. The behavior of load tap changer (LTC) transformer and generator field protection or over excitation limiter (OXL) are some of the most important slower dynamics to be taken in to the consideration for voltage stability studies.

The use of long term dynamic simulation technique, including the effect of slow acting devices allows utility engineer to develop a better understanding of the true limits of their system. Longer term dynamic simulations require good models of the slow dynamics associated with voltage collapse. Better component model give utility engineers the ability to conduct detailed studies that more realistically reflect the behavior of power systems.

In this chapter modeling of over excitation limiter (OXL) and load tap changer (LTC) transformer relevant to voltage stability studies have been discussed. Their effect on voltage stability has been demonstrated on the 11-bus test system and 39-bus New England system.

3.2 Modeling

3.2.1 Over excitation limiter (OXL)

The reactive power capability of the generators must be modeled in sufficient detail to capture their behavior in the period leading up to a voltage collapse The *Field Current*

Limit is of particular concern when studying voltage stability This limit is enforced by the generator overexcitation limits (OXL) control function. When the field current goes above its limit, typically the OXL control resets the field excitation voltage to a value that will bring the field current within limits.

Figure 3.1 shows the block diagram of the over excitation system [1], which has been used in the study. A typical characteristics can be shown in the figure 3.2. In figure 3.1 & 3.2, I_{FLM1} and I_{FLM2} are the upper and lower limits of the field current I_{fd}.

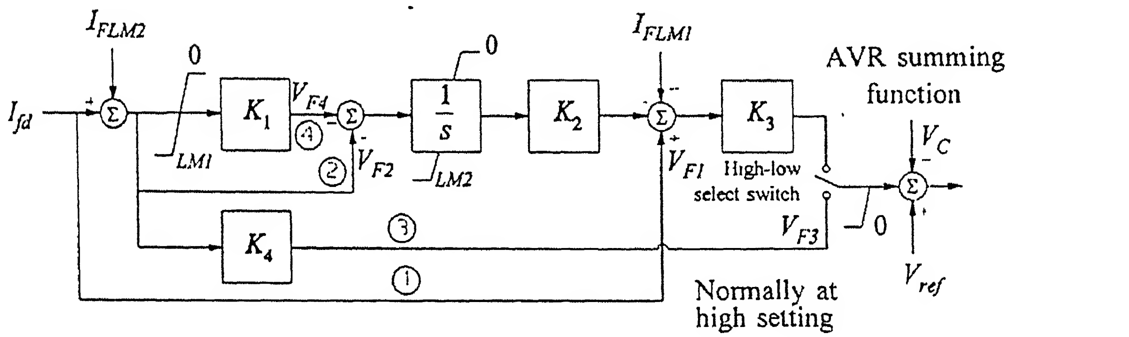

Figure 3.1 Block diagram of Over Excitation Limiter (OXL).

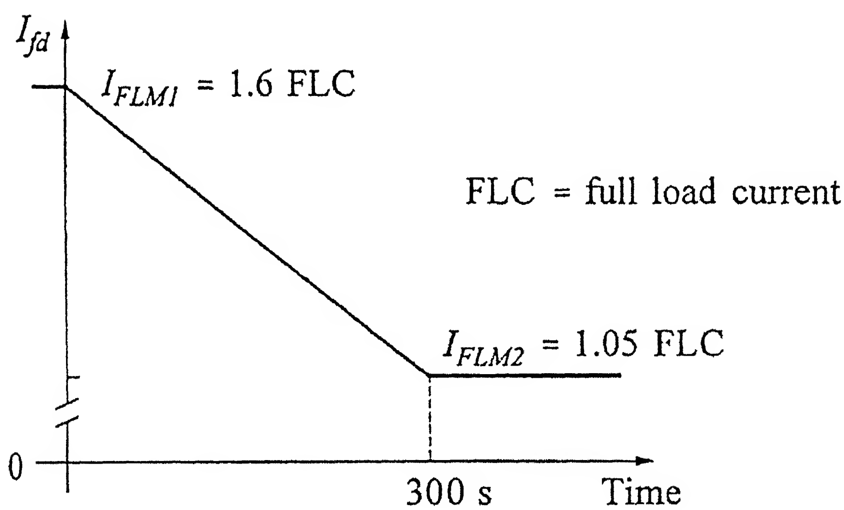

Figure 3.2 Over excitation limiter(OXL) characteristics

As shown in figure 3.2, high setting provides almost instantaneous limiting at 1.6 times full load current (FLC). A low settings of 1.05 times FLC in conjunction with

ramp timing function provides a limiting action with the time delay dependent on the level of field current. For example a field current level of 1.2 times FLC will be allowed for 150 secs followed by a reduction in current level to 1.05 times FLC over next 100 secs.

Referring to the block diagram of figure 3.1 when I_{fd} exceeds the high setting I_{FLM1}, the signal V_{F1} of control loop 1 acts to reduce excitation instantaneously. When the field current is below I_{FLM1}, the limiting action is through the control loop 2. The magnitude of the control signal V_{F2} and the value of gain K_2 determine the time delay and ramping action. When the field current is below I_{FLM2} the signal V_{F4} helps to reset rapidly the integrator output to zero.

3.2.2 Load tap changer (LTC)

Most voltage instabilities are initiated by the loss of infeed into an area, causing a drop in voltage. Since the system loads are generally voltage dependent, the voltage drop will cause a reduction in the power consumed by the loads. This is referred to as *load relief,* since it will tend to reduce the stress on the system. However, the action of ULTCs and distribution system voltage regulators will tend to bring the load voltages back to their base point. These devices will respond over the period of several minutes following the contingency, and will cause the power consumed by the loads to return towards their pre-contingency level. This will cause further stress on the system and can eventually lead to a voltage collapse condition.

The LTCs have a secondary effect on the voltage collapse. When trying to boost the low side voltage, they *drain* reactive power from the high side system and *pump* it to low side. This will place even greater stress on the transmission system and further aggravate the voltage instability.

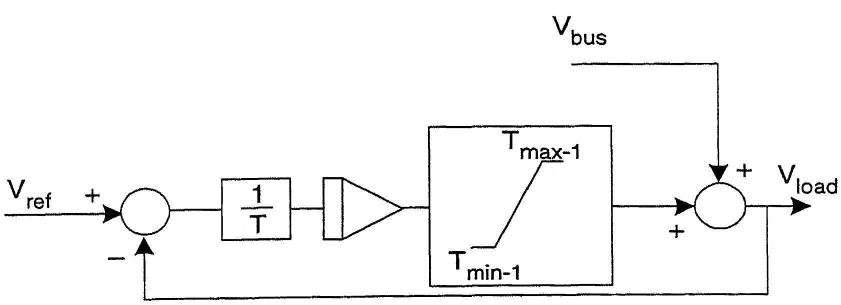

Figure 3.2 Block diagram of Load Tap Changer (LTC)

For voltage stability analysis, the actions of the LTCs must be modeled accurately to assess voltage collapse conditions. The LTCs must be modeled with their actual tap range and size, voltage controls and deadbands, and settings for tap delay and tap motion time.

In order to represent in a simplified way the effect of limited voltage control device tap range and the time required to change taps, the model shown in figure 3.3 has been used. The quantity labeled V_{bus} is to system bus voltage, while V_{load} is the voltage that is applied to the load model. V_{ref} is normally set to 1.0 p.u.

3.3 Case Study

To study the impact of OXL, LTC actions and load levels on voltage stability, the long term dynamic simulation were done on the 11-bus test system and 39-bus New England test system. The detail of these two systems are given in Appendix-A & B, respectively. The simulation results for the two systems are given below.

3.3.1 11-Bus test system

This system as given in Appendix A, is highly stressed and consists of high level of power transfer from generation rich region towards an area with both heavy loads and considerable amount of local generation. This system considered here is based on the system described in references [1, 3, 16] for the analysis of various aspects of the voltage stability.

For the study, four different load levels were considered. The load levels are shown in table 3.1, which is the same as table A.4.

Table 3.1 Different load levels

Load level	Bus 08		Bus 11	
	MW	MVAR	MW	MVAR
1	3320	1030	3435	985
2	3365	1058	3480	1010
3	3385	1090	3500	1030
4	3395	1100	3530	1040

The Over Excitation Limiter (OXL) is included for generator 3 only. The under load tap changer (ULTC) is considered included for transformer T6 between bus 10 and 11. The tap changer data is given in appendix A.

The disturbance considered is the loss of one of the lines between buses 6 and 7. The voltage stability of the system has been investigated with the following representations of loads at buses 8 and 11:

The load at bus 11 is modeled as constant power for both active and reactive components; the action of the ULTC transformer (T6) supplying this load is modeled in detail. The active and reactive power load at bus 8 is modeled as,

- Case 1 : Constant active and reactive power (CARP) load model.
- Case 2 : ZIP Load model.
- Case 3 : Generic Dynamic load model (GDLM).

The transformer T4 supplying this load is assumed to have a fixed tap.

The long term dynamic simulation has carried out with the help of NETOMAC (NEtwotk TOrsion MAchine Control) software for the period of 400 sec. The results for the three cases and the four load levels are given below.

Case -1:

Figures 3.4, 3.5 & 3.6 show the time responses of the voltages at buses 11, 8, and 3 following the loss of one of the lines between buses 6 and 7, for each of the load levels for case 1. The plots of generator G3 field current, reactive power output, and terminal voltage are also shown in these figures.

The effect of the loss of the line is to cause the system voltage to drop initially. For **load level 1**, the ULTC action of transformer T6 restores bus 11 voltage to nearly its reference value in about 100 seconds. Field current of G3 remains below its continuous limit and the terminal voltage is maintained at the initial value by the AVR. The voltages at buses 10 and 7 settle at values below the predisturbance values. The system is however, voltage stable.

With the **load level 2** the voltage at bus 11 restores to nearly its reference value in about 100 seconds. However, the reactive power demand of the generator 3 is

now higher and the field current of the generator 3 exceeds its limit. The over excitation limiter of generator3 starts ramping the field current down at about 340 seconds. This in turn triggers the following chain of events

- The terminal voltage of G3, which is no longer being controlled by the AVR drops.
- Voltage at buses 8 ,11 and 7 drop.
- The demand for reactive power on the generators increases. The OXL on G3 continues to hold the, field current at its limit and the terminal voltage of G3 continues to drop.
- The ULTC on T6 operates again and the voltage at bus 11 sets slightly below its predisturbance value.
- Voltage at bus 08 settles below its predisturbance value.

With the **load level 3** the reactive power demand is higher than the previous case and the field current of the generator 3 is now well above its maximum limit. The over excitation limiter of generator3 starts ramping down the field current at quite earlier than the previous case at about 140 seconds and then chain of events described in previous case occurs but in this case the tap changer reaches its maximum position at about 190 second and now the voltage at bus 11 no longer maintained by the tap changer. It starts dropping down and it settles well below its predisturbance value. The simulation result with the **load level 4** was also found similar to the load level 3.

<u>Case -2</u>

This case has been studied with the ZIP load model at bus 08. The results can be seen in the figures 3.7, 3.8 & 3.9 for load level 1, load level 2 and load level 3, respectively. In this case, the effect of loss of the line is to cause the active and reactive power component of the load at bus 08 to drop but it settles at higher value compared to the case 1. The results obtained are quite similar to the case 1 but voltage start dropping down very early than case 1 and also the voltage settles at lower value compared to case 1.

<u>Case 3</u>

This case has been studied with the first order generic dynamic load model at bus 08. The results can be seen in the figures 3.10, 3.11 & 3.12 for load level 1, load level 2

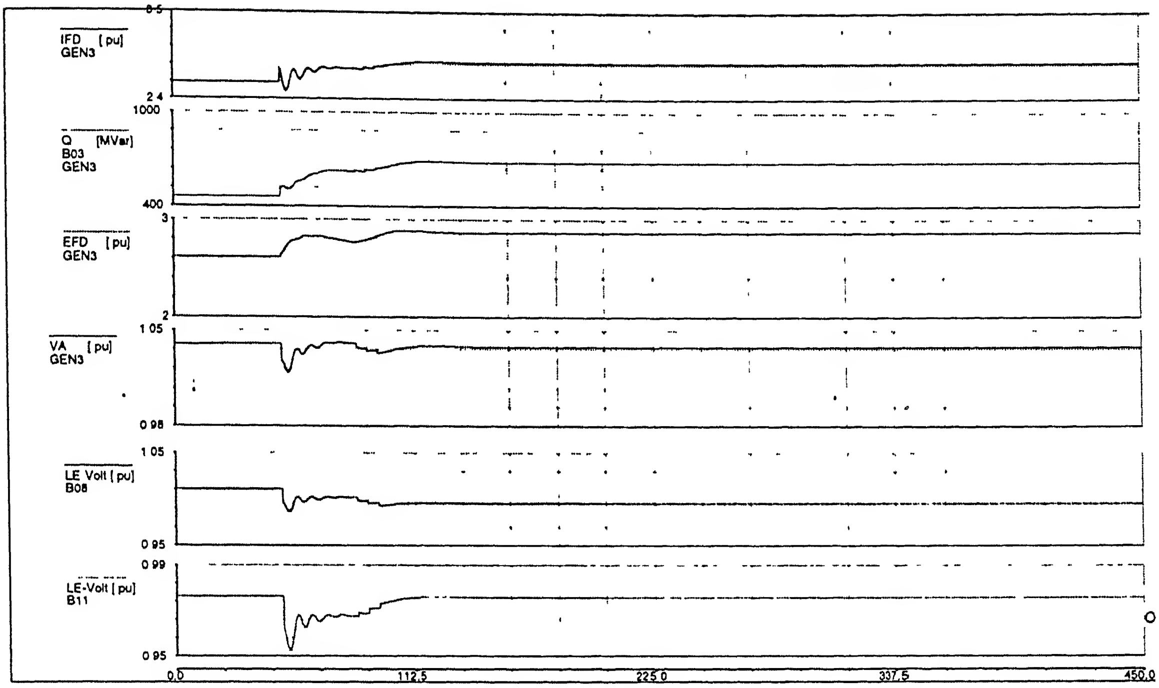

*Figure 3.4 Simulation results of **case 1 & load level 1**(Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

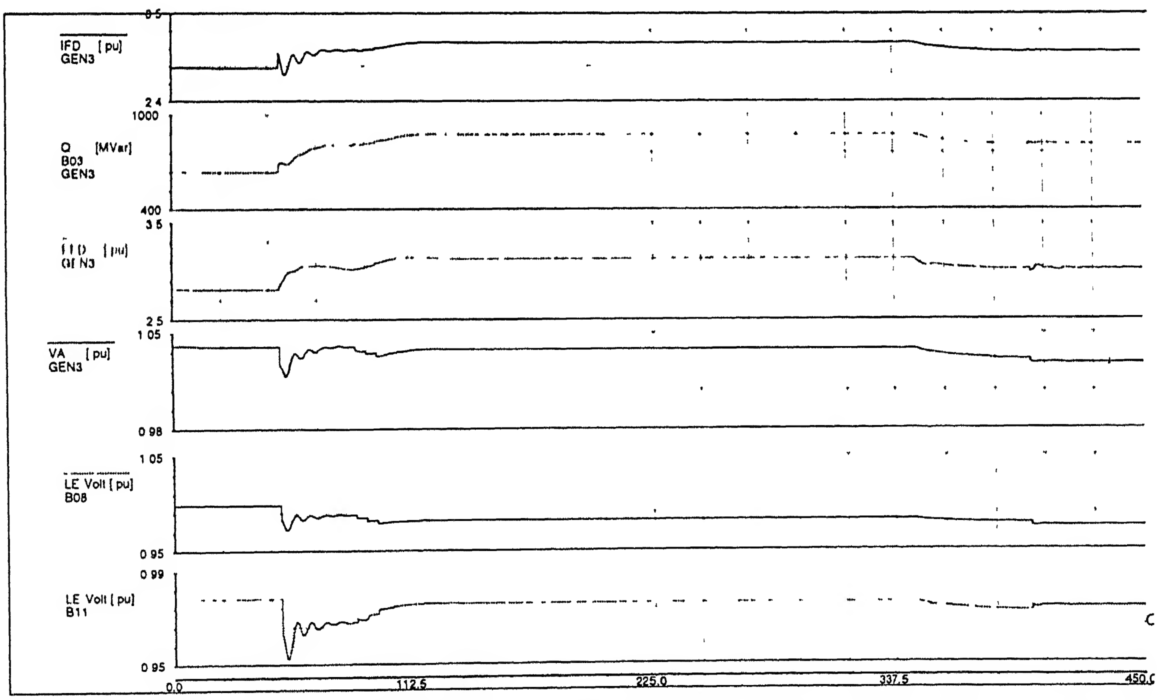

*Figure 3.5 Simulation results of **case 1 & load level 2** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

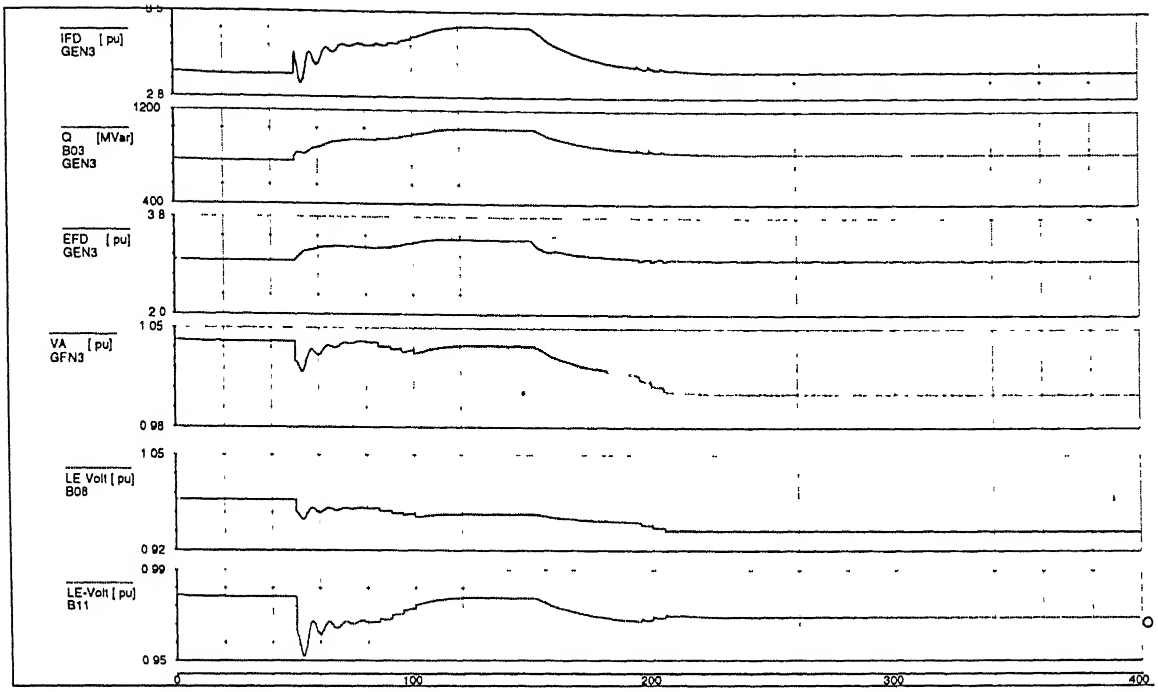

*Figure 3.6 Simulation results of **case 1 & load level 3** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

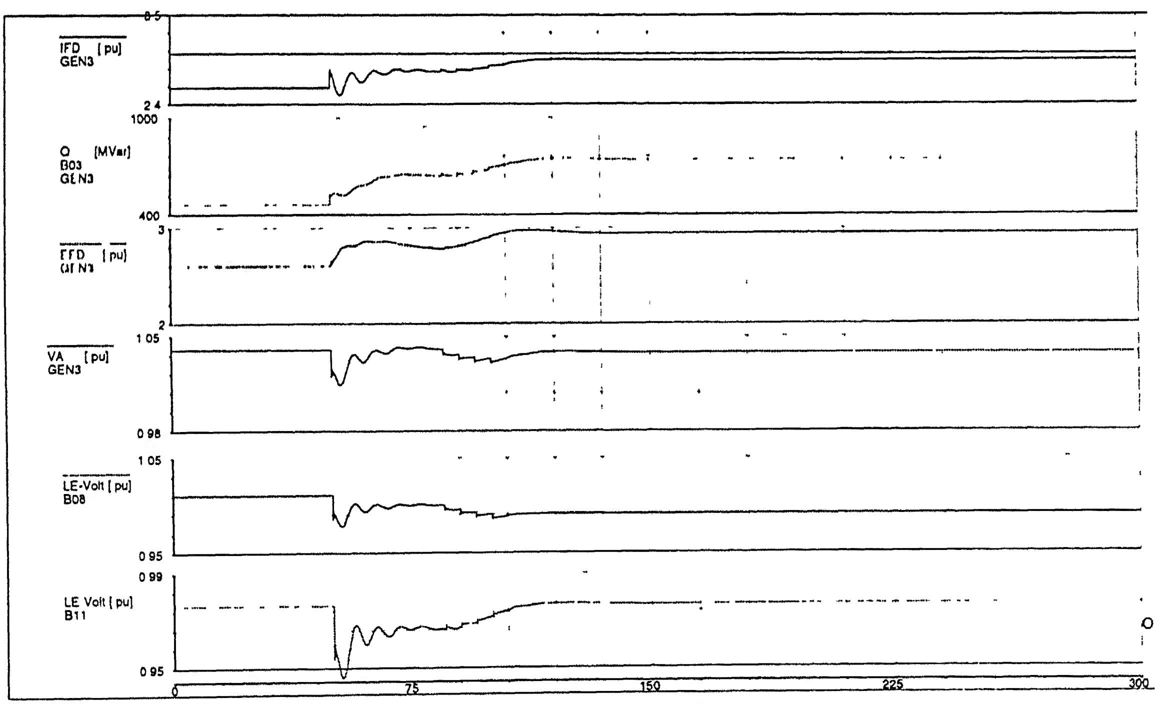

*Figure 3.7 Simulation results of **case 2 & load level 1** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

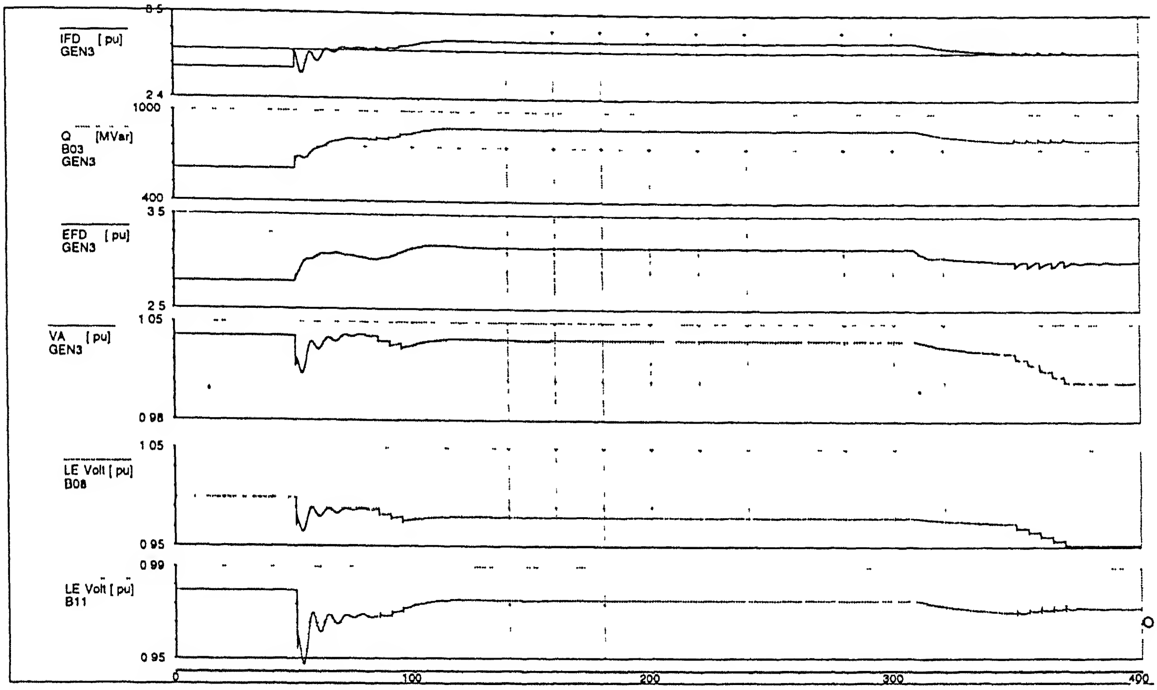

Figure 3.8 Simulation results of ***case 2 & load level 2*** *(Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

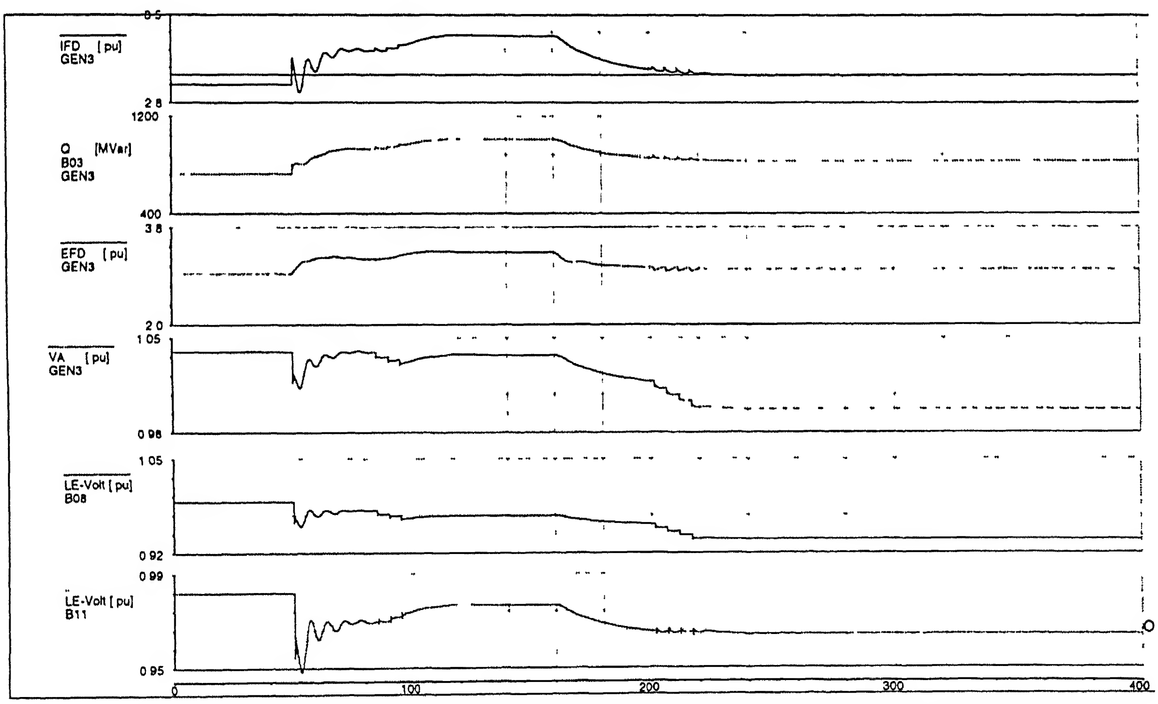

Figure 3.9 Simulation results of ***case 2 & load level 3*** *(Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

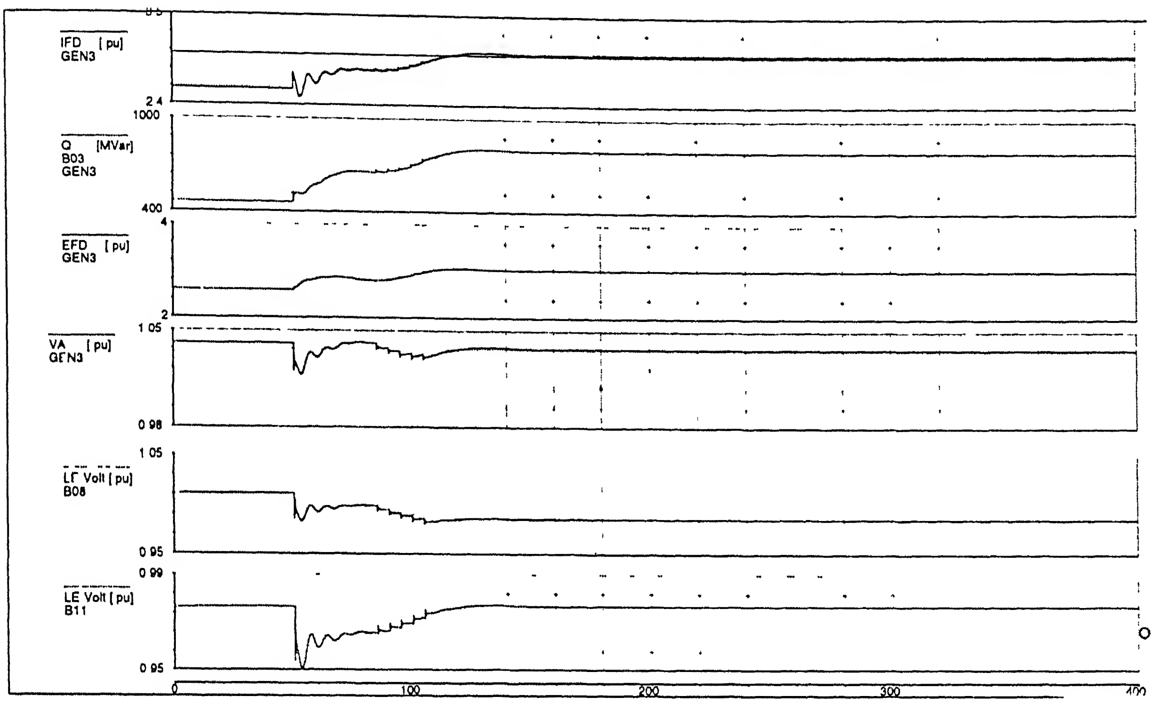

*Figure 3.10 Simulation results **of case 3 & load level 1** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

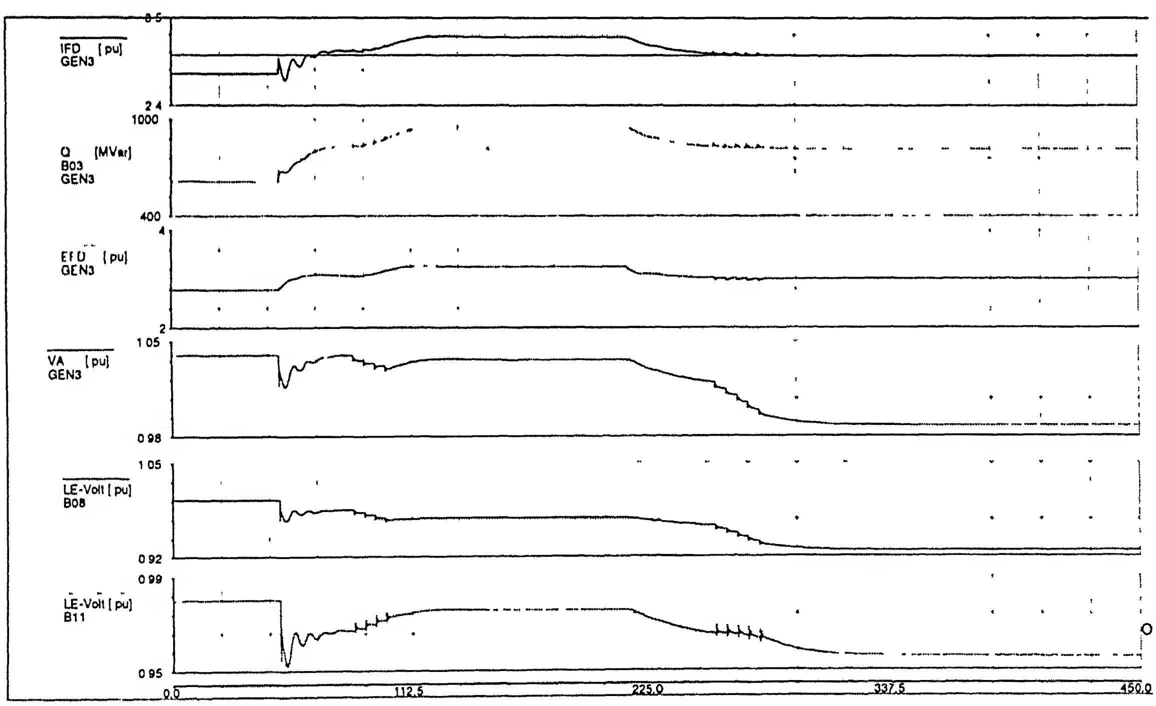

*Figure 3.11 Simulation results **of case 3 & load level 2** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

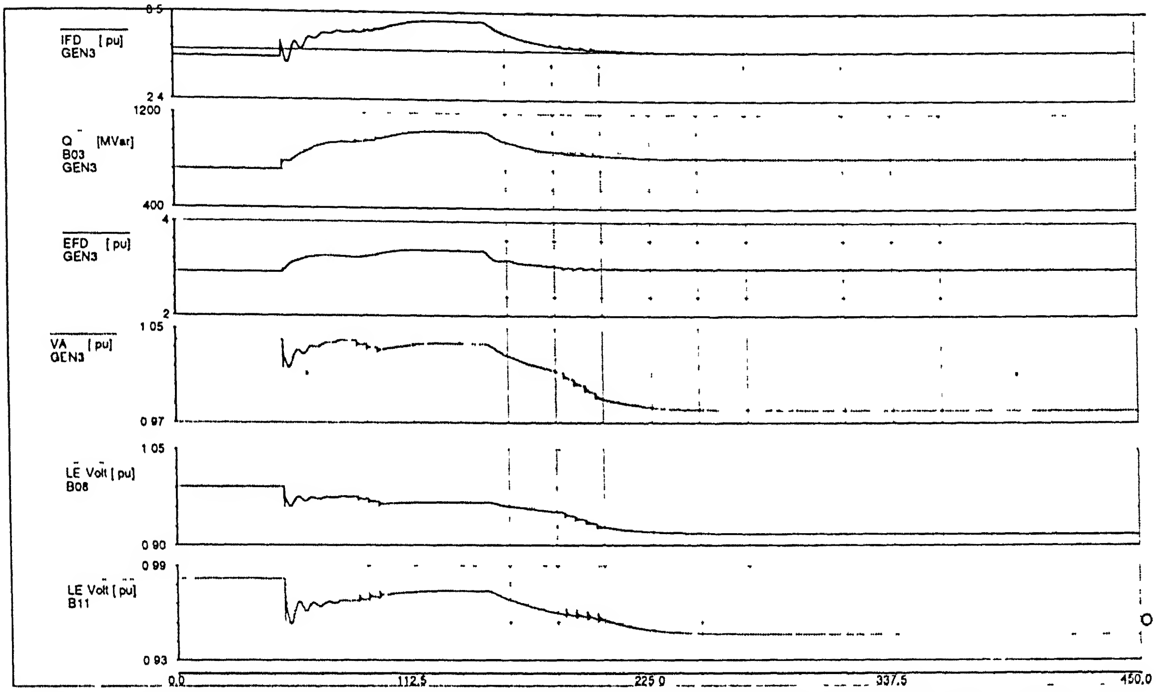

*Figure 3.12 Simulation results of **case 3 & load level 3** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

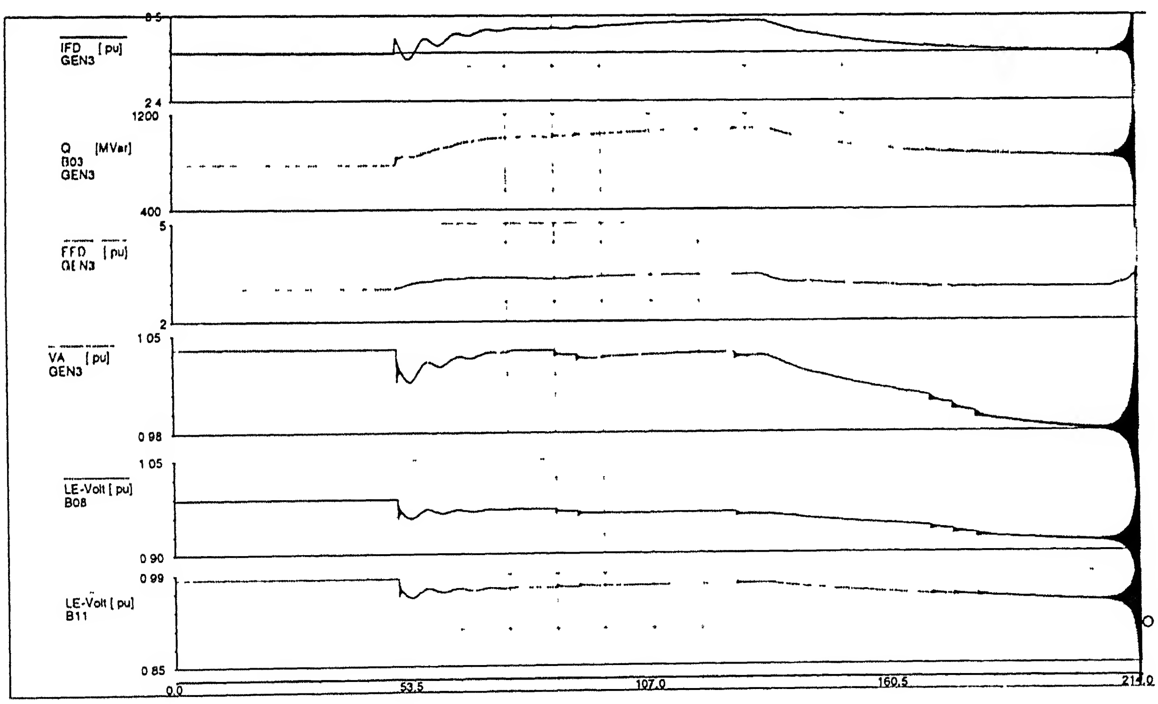

*Figure 3.13 Simulation results of **case 3 & load level 4** (Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

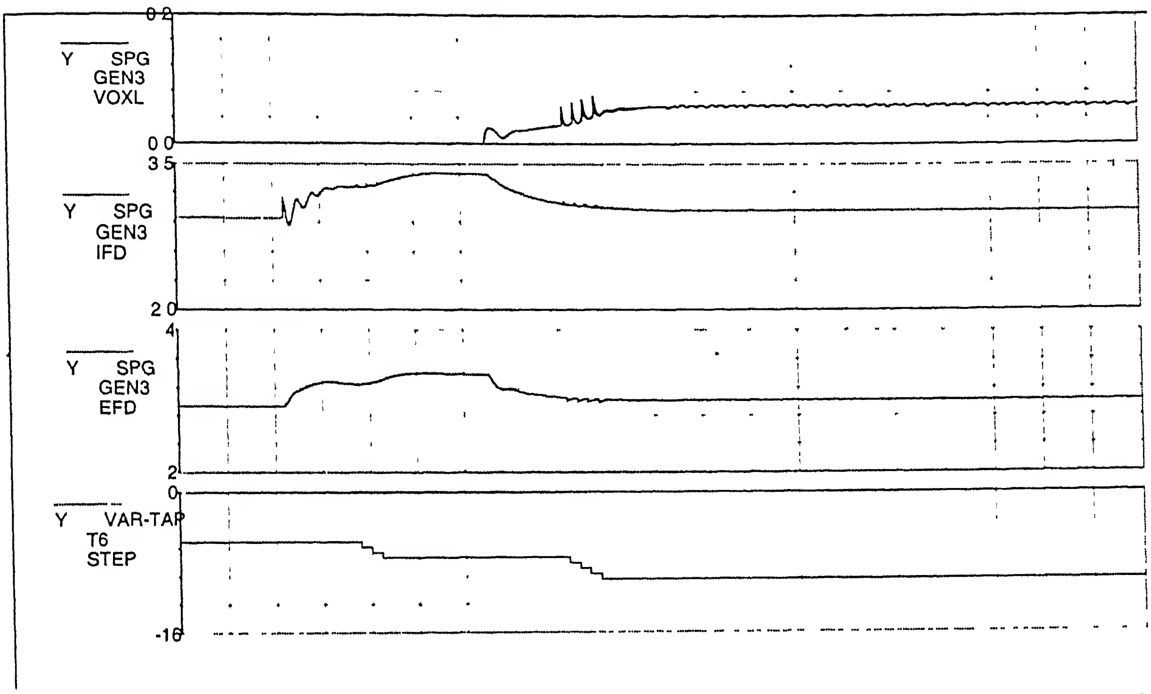

Figure 3.14 Simulation results of ***case 3 & load level 3*** *(Generator 3 OXL signal, field current, field volatge and tap changer step at load bus 11)*

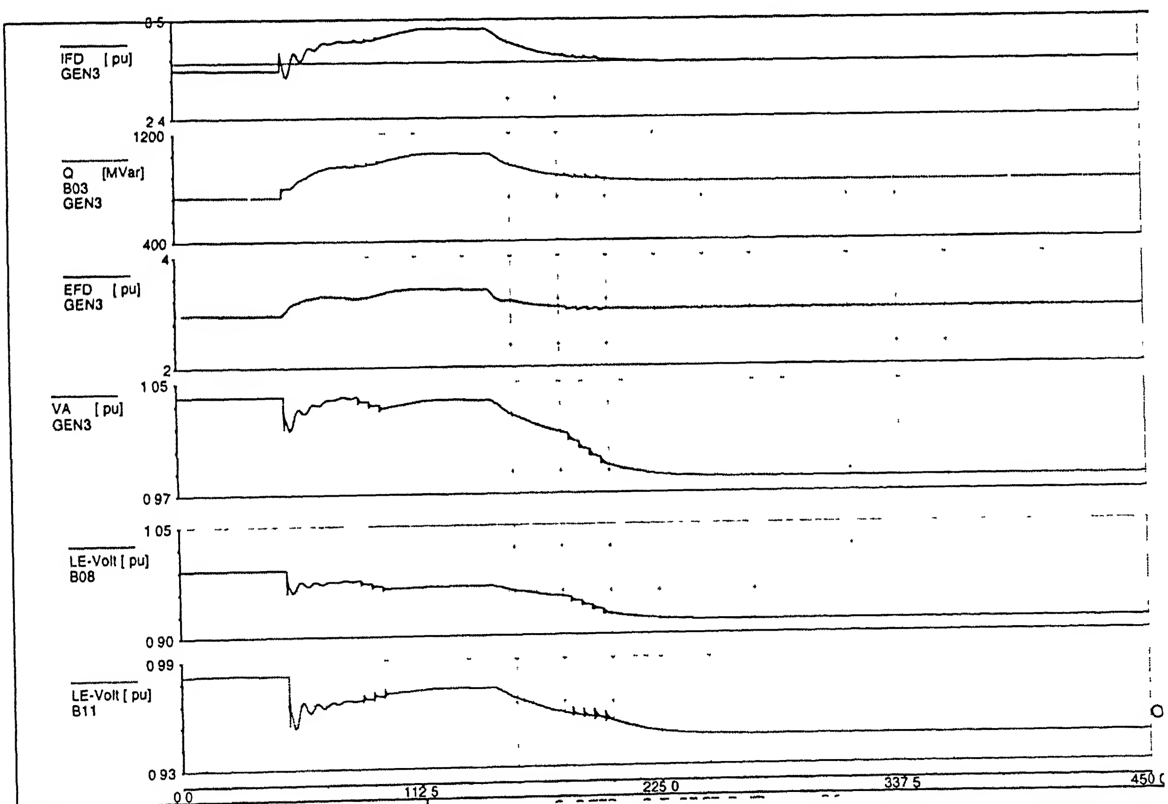

Figure 3.15 Simulation results of ***case 3 & load level 3*** *(Generator 3 exciter current, Q output, field voltage & terminal voltage and voltage at load bus 08 & 11.)*

and load level 3 respectively. In this case, the results obtained are more or less similar to the first two cases but for the load level 3 the ULTC on transformer T6 tries to maintain bus 11 voltage to its predisturbance value but the net effect of each tap movement is to reduce bus 11 voltage further rather than increasing it. This can be seen in the figures 3.14 and 3.15. In this case, voltages settle to even lower value compared to the first two cases.

For the **load level 4**, system voltage completely collapses at 190 sec. The response can be seen in the figure 3.13. The same case has been studied with other static load models but the results are almost same as that of the load level 3.

3.3.2 39 Bus New England test system

New England test system consists of 10 generators, 39 buses, 19 load buses, 12 transformers and 46 branches. The line data, bus data, the machine parameter, the excitation system data, and governor system data can be found in Appendix B.

The disturbance considered in this system is the outage of transmission line between buses 16 and 19. Due to outage of this transmission line, the two generators, Gen. 4 and Gen. 5 knocks off from the rest of the system. Simulation has been done with and without consideration of the field current limiter of generators and with different load models.

a) Without OXL :

In case of outage of line 16-19, the system suffer a significant loss of generation. The demand for the active and reactive power increases in the remaining system. The field current of all the generator are forced to increase and now generator expected to deliver more reactive power as compared to healthy case. The voltage stability of the system has been investigated with following representation of loads at all the buses.

Case 1: Constant active and reactive power load model.

Case 2: ZIP Load model.

Case 3: Generic dynamic load model .

Case 1:

Figures 3.16, 3.17, 3.18 & 3.19 show the time response of the system for the **case 1** following loss of the transmission line between bus 16 and 19. The effect of loss of

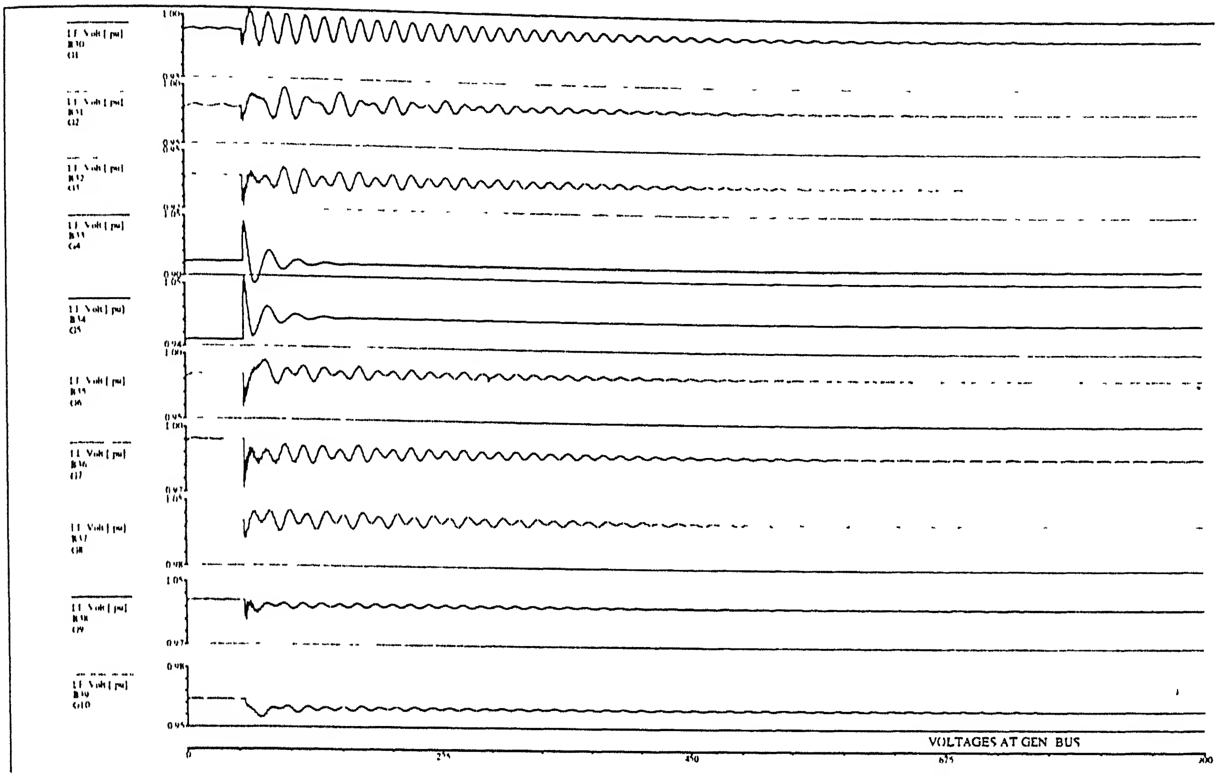

Figure 3.16 Generator terminal voltages for constant power load model w/o OXL

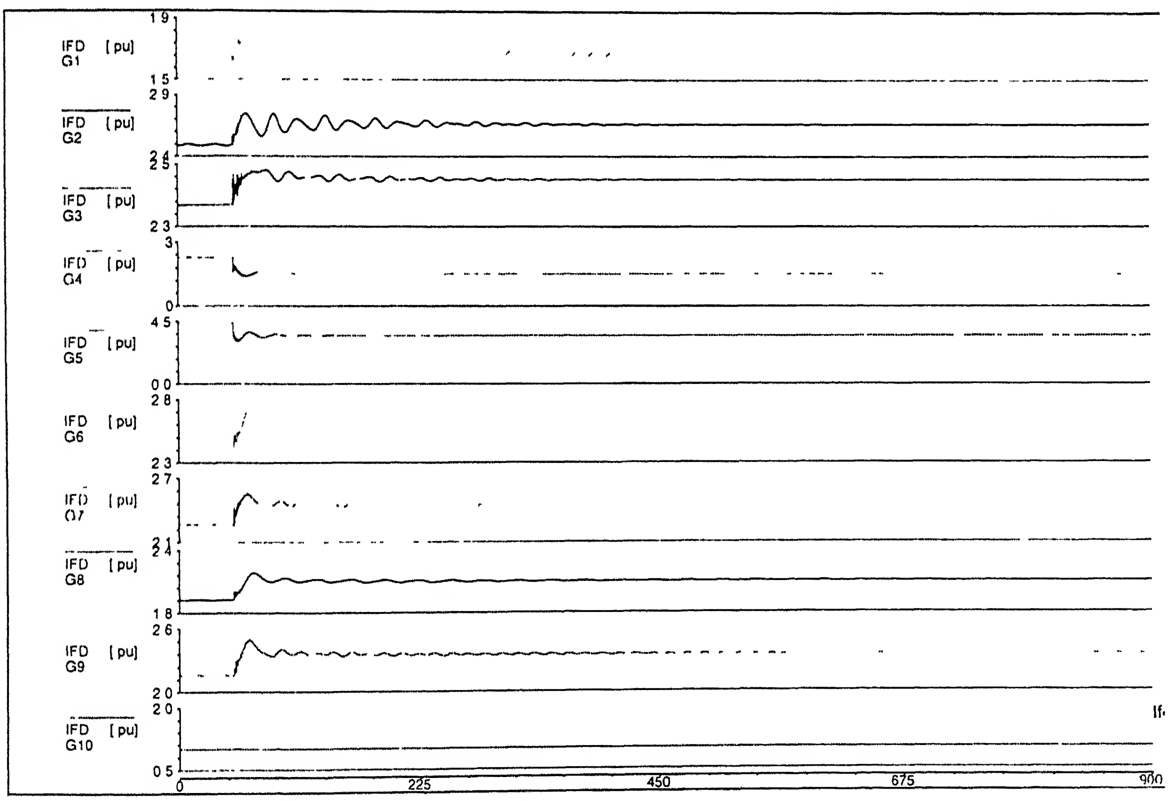

Figure 3.17 Field current of generators with constant power load model w/o OXL

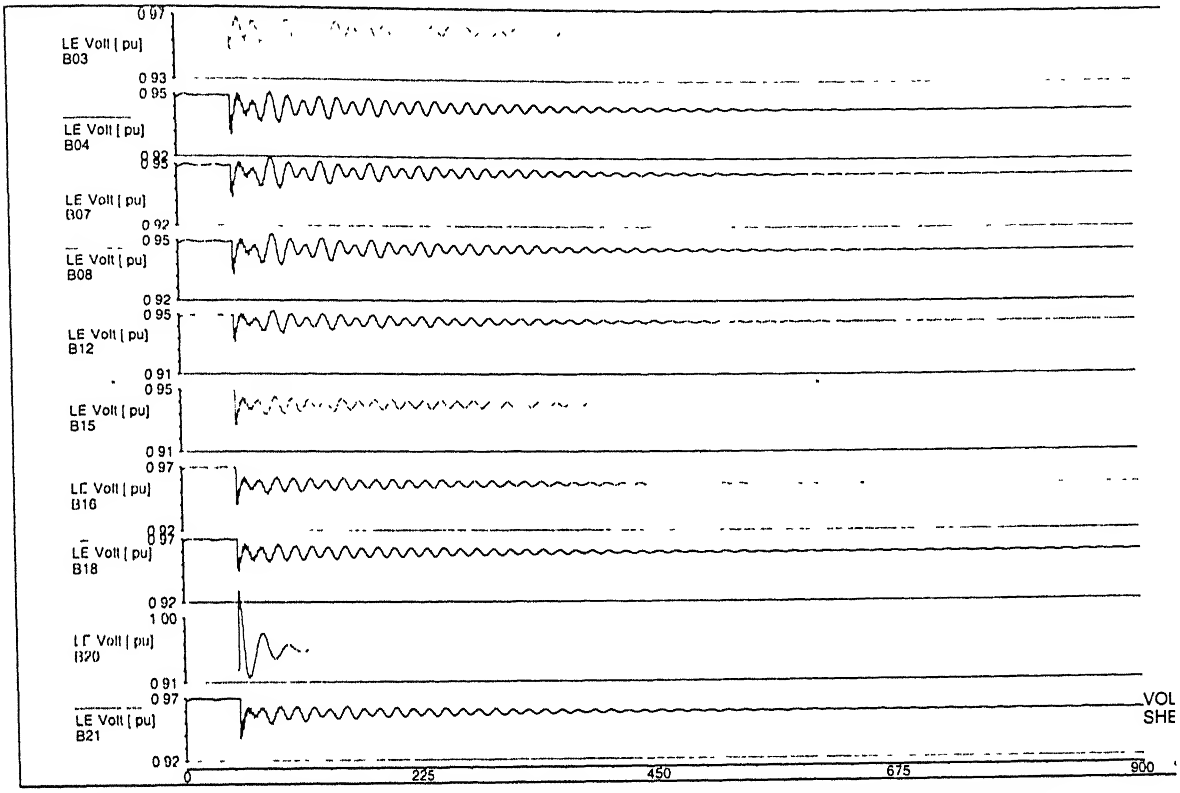

Figure 3.18 Voltages at load bus with ***constant power load model w/o OXL***

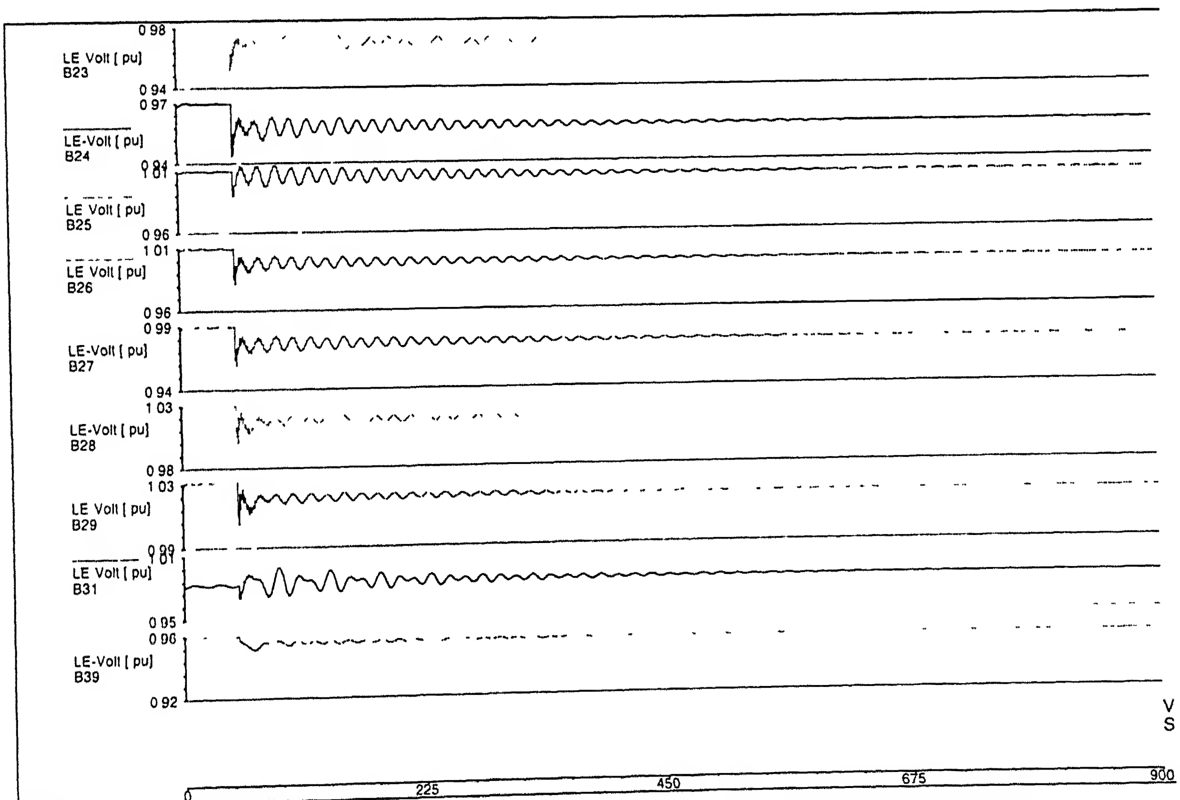

Figure 3.19 Voltages at load bus ***with constant power load model w/o OXL***

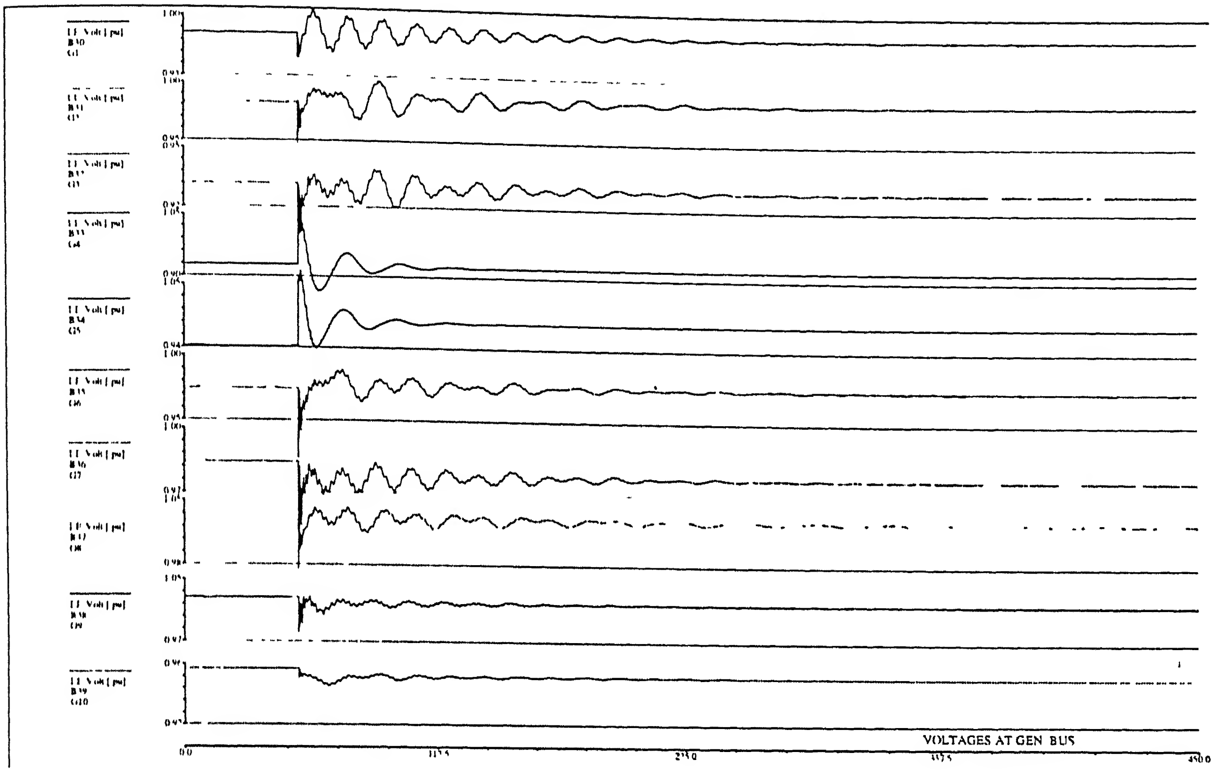

Figure 3.20 Generator terminal voltages for ***ZIP load model w/o OXL***

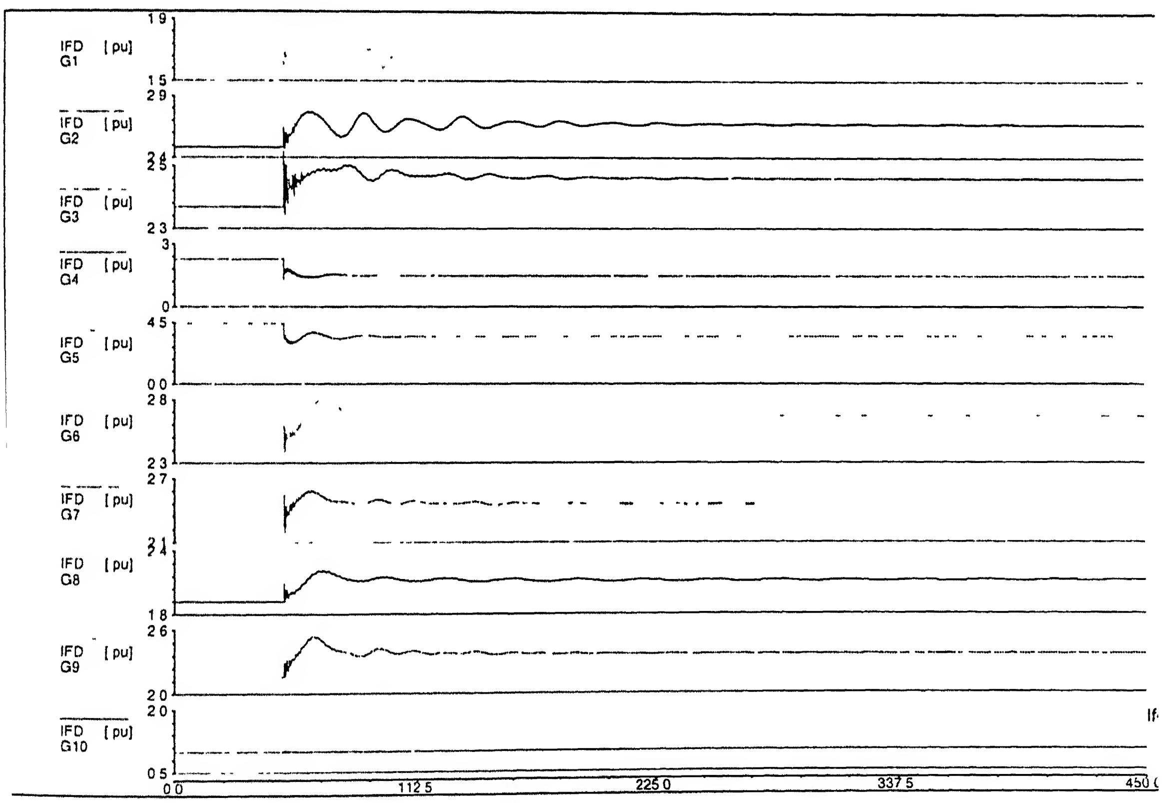

Figure 3.21 Field current of generators with ***ZIP load model w/o OXL***

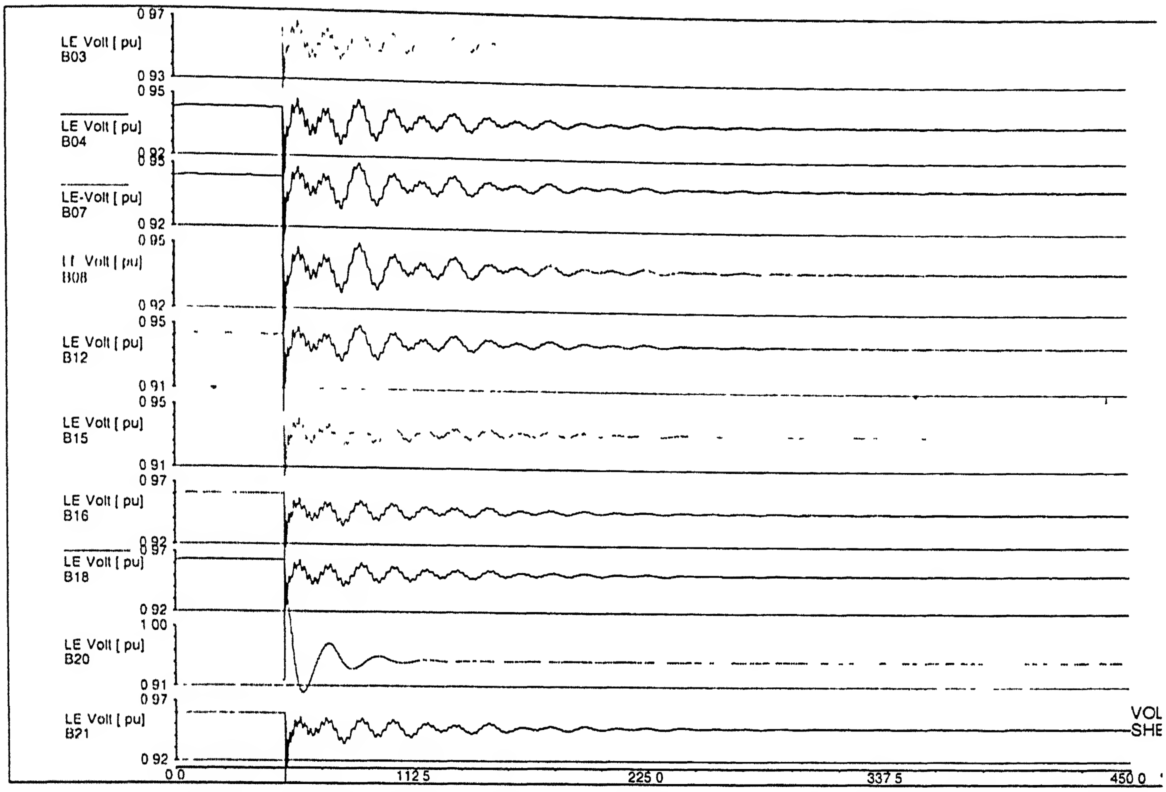

*Figure 3.22 Voltages at load bus with **ZIP load model w/o OXL***

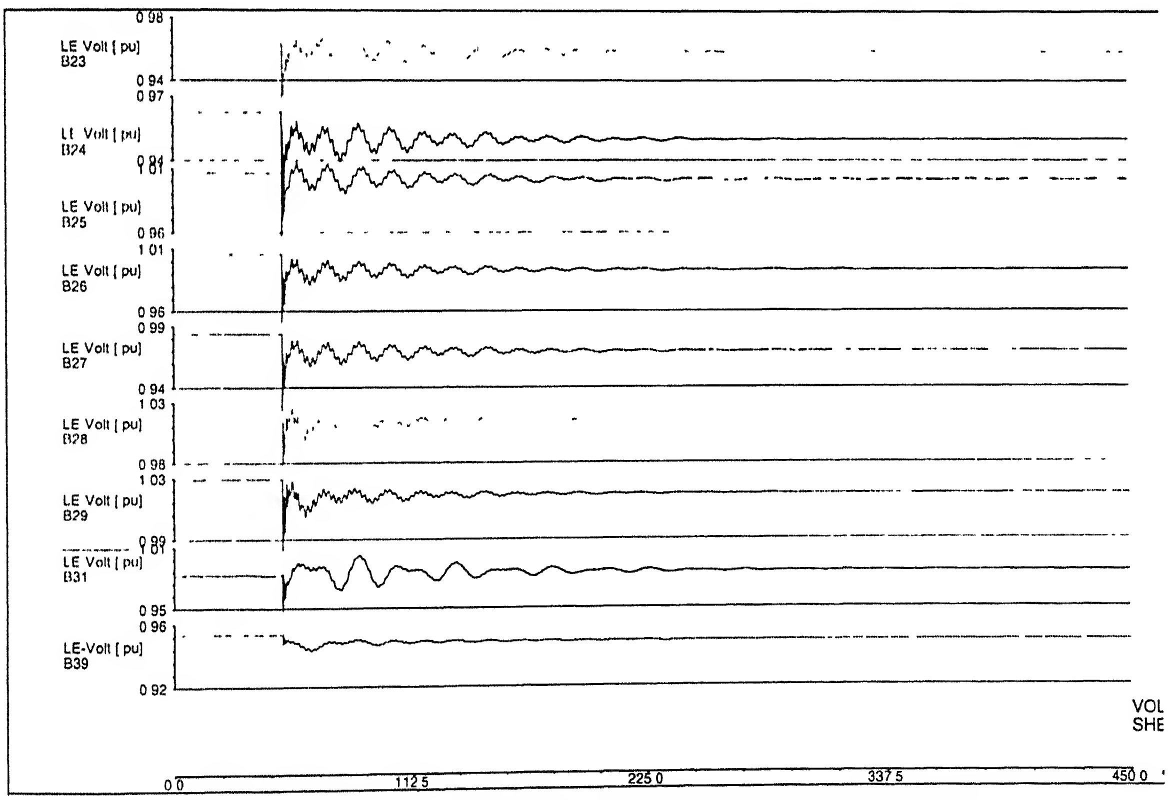

*Figure 3.23 Voltages at load bus with **ZIP load model w/o OXL***

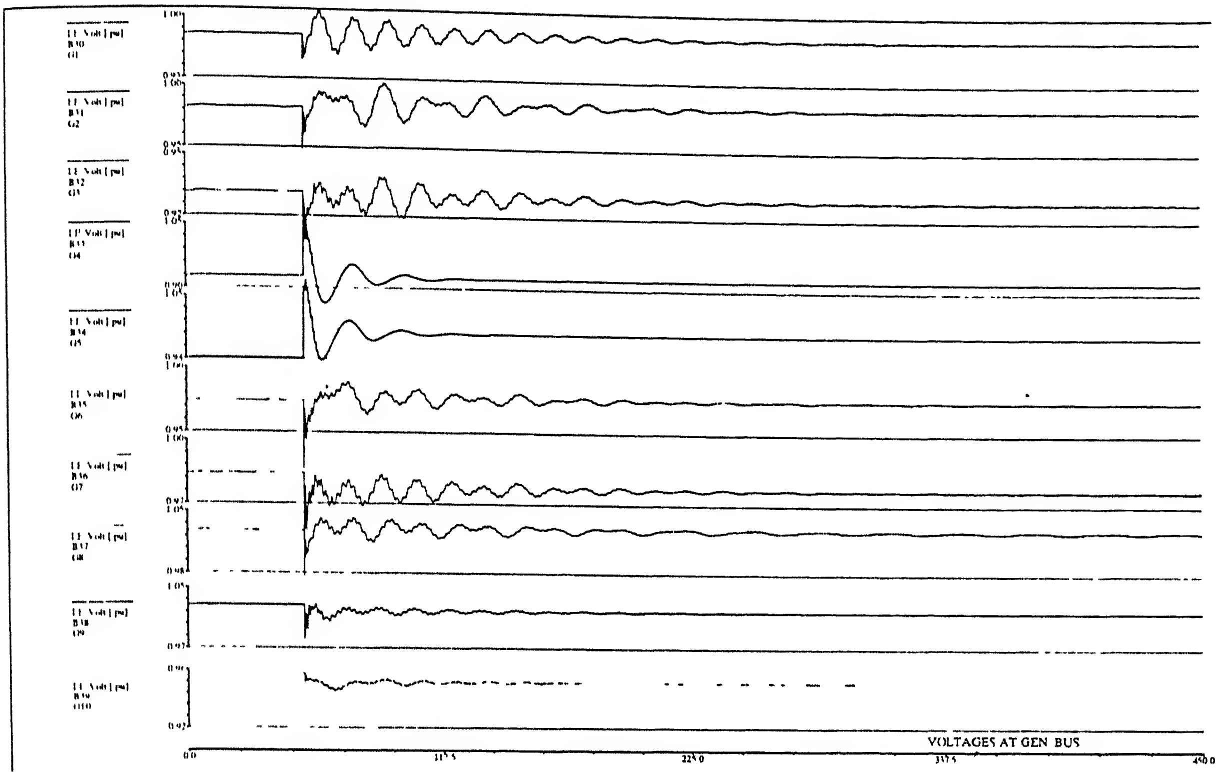

*Figure 3.24 Generator terminal voltages for **GDLM load model w/o OXL***

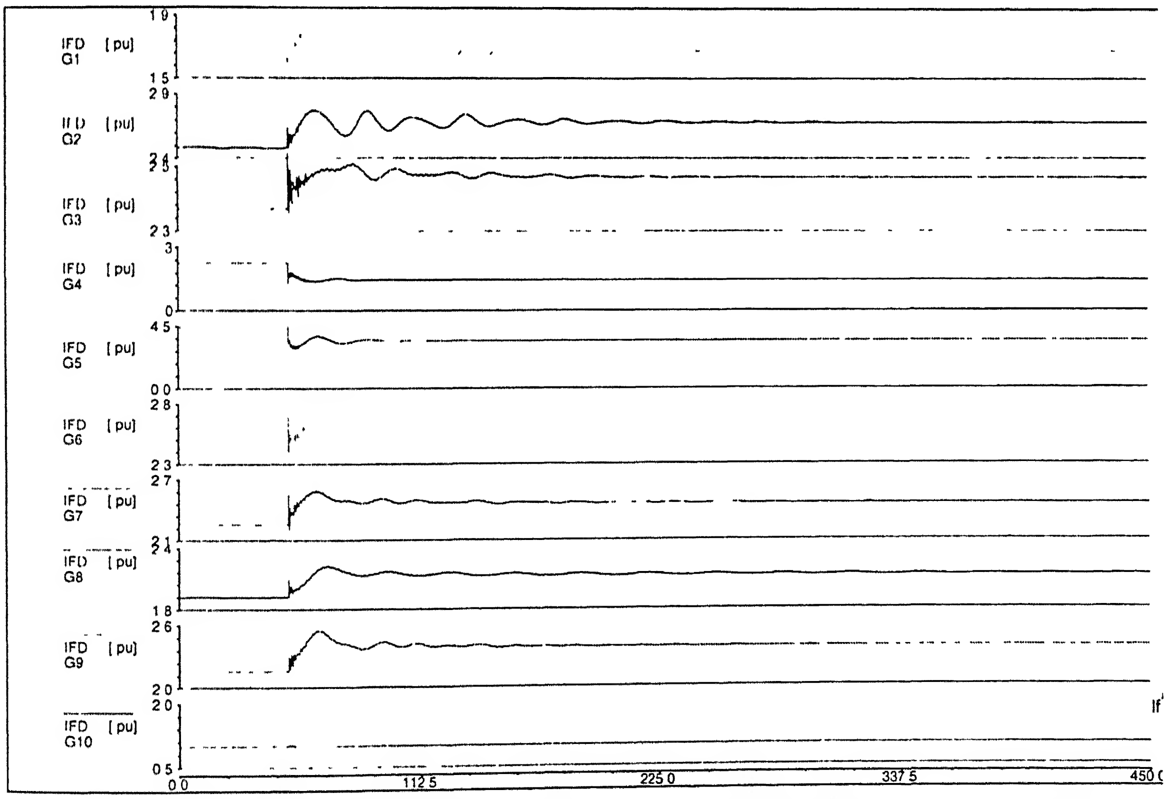

*Figure 3.25 Field current of generators with **GDLM load model w/o OXL***

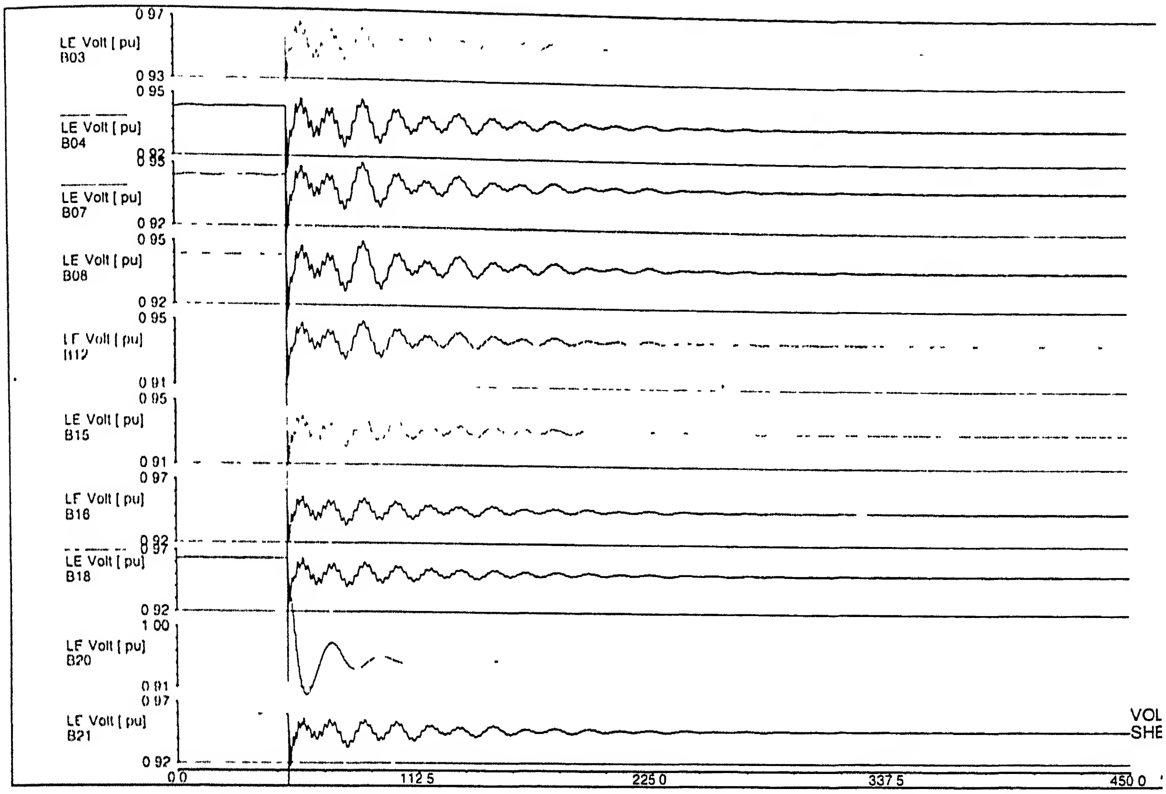

Figure 3.26 Voltages at load bus with ***GDLM load model w/o OXL***

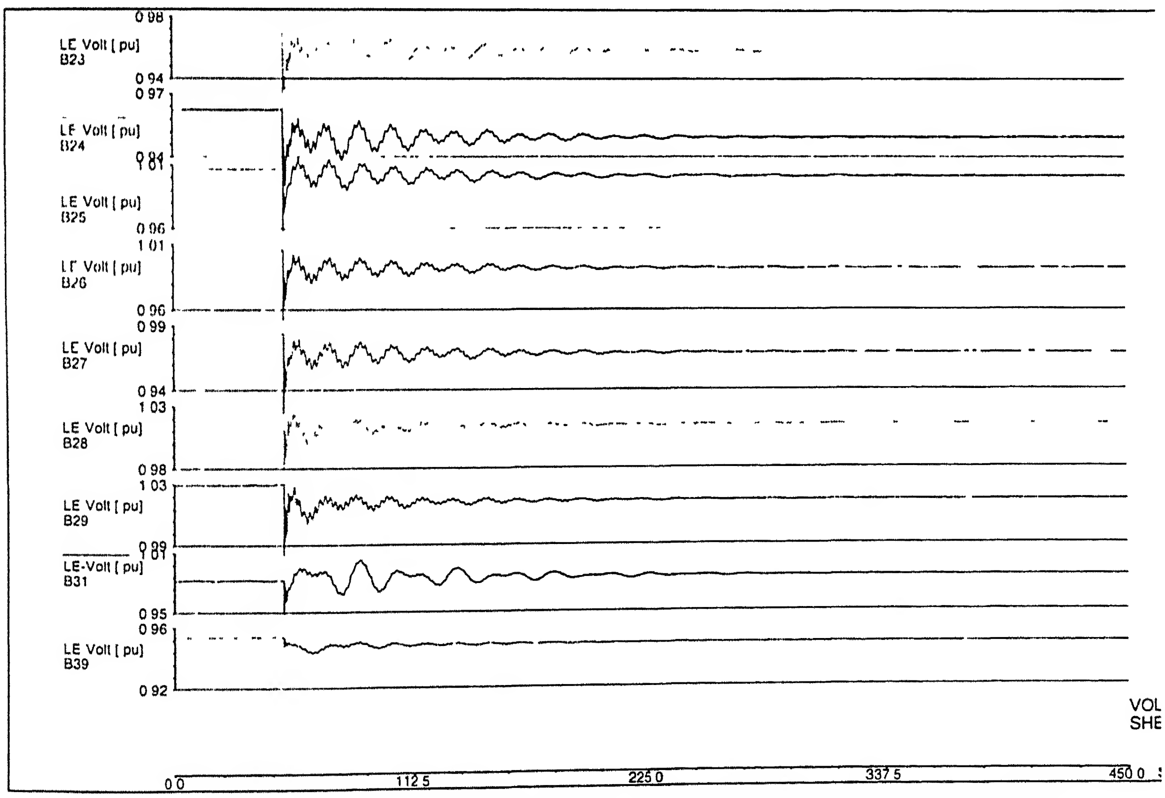

Figure 3.27 Voltages at load bus with ***GDLM load model w/o OXL***

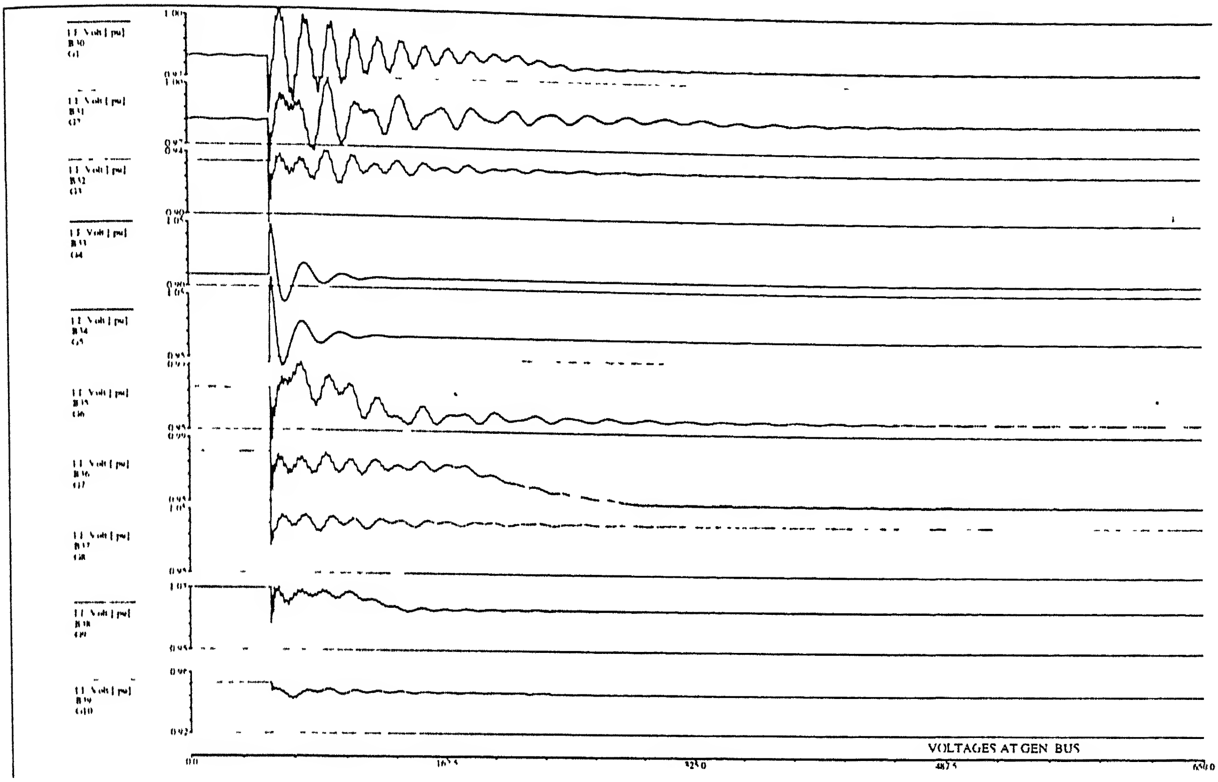

Figure 3.28 Generator terminal voltages for ***GDLM with OXL***

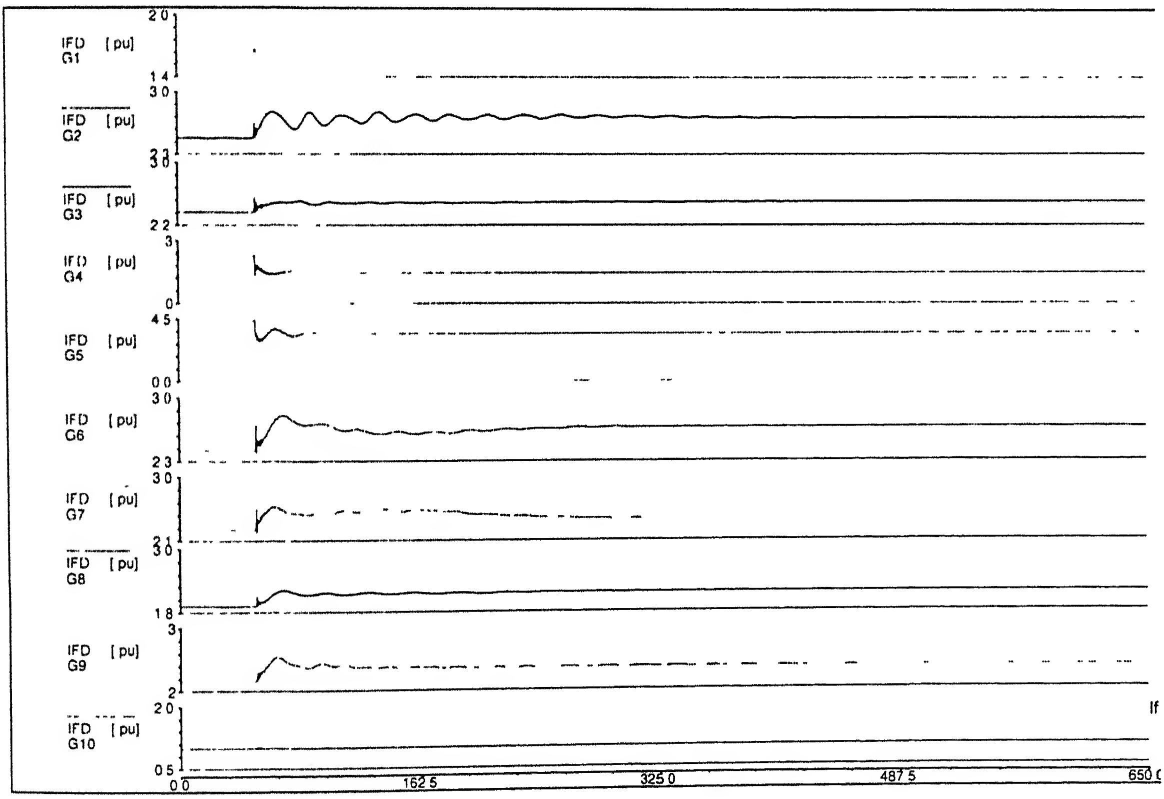

Figure 3.29 Field current of generators with ***GDLM with OXL***

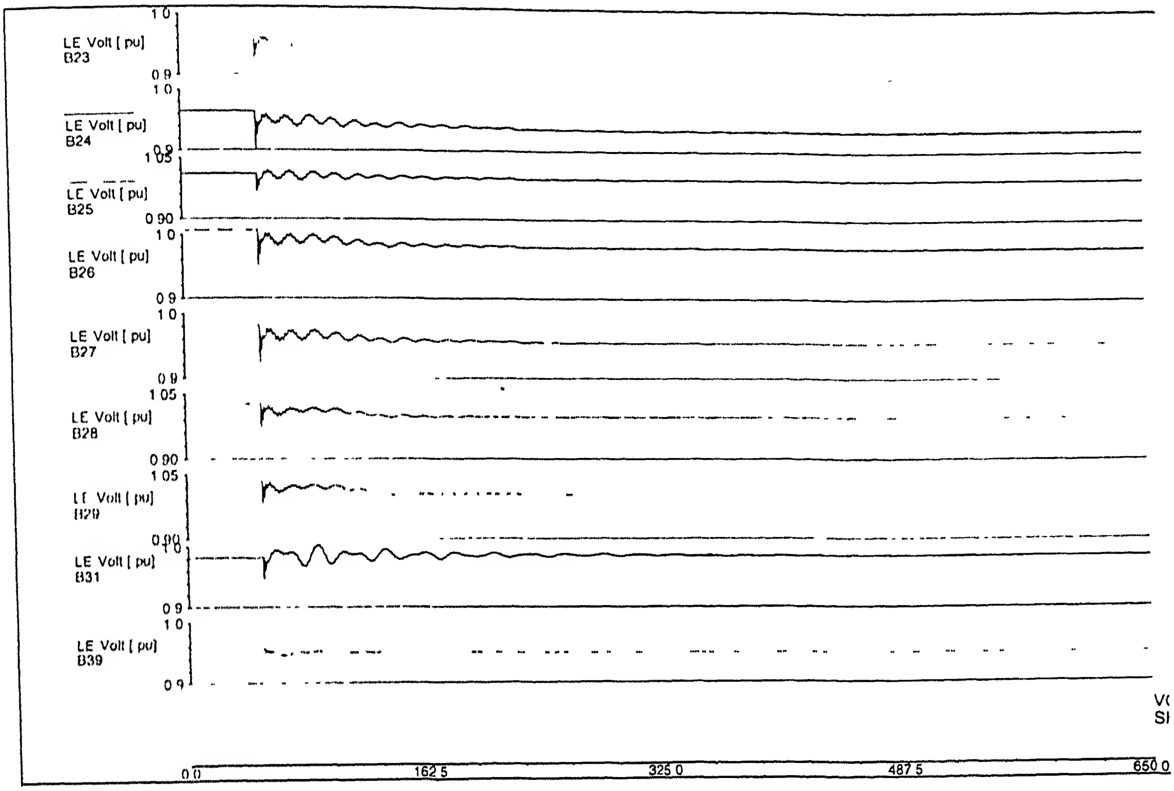

Figure 3.30 Voltages at load bus with ***GDLM with OXL***

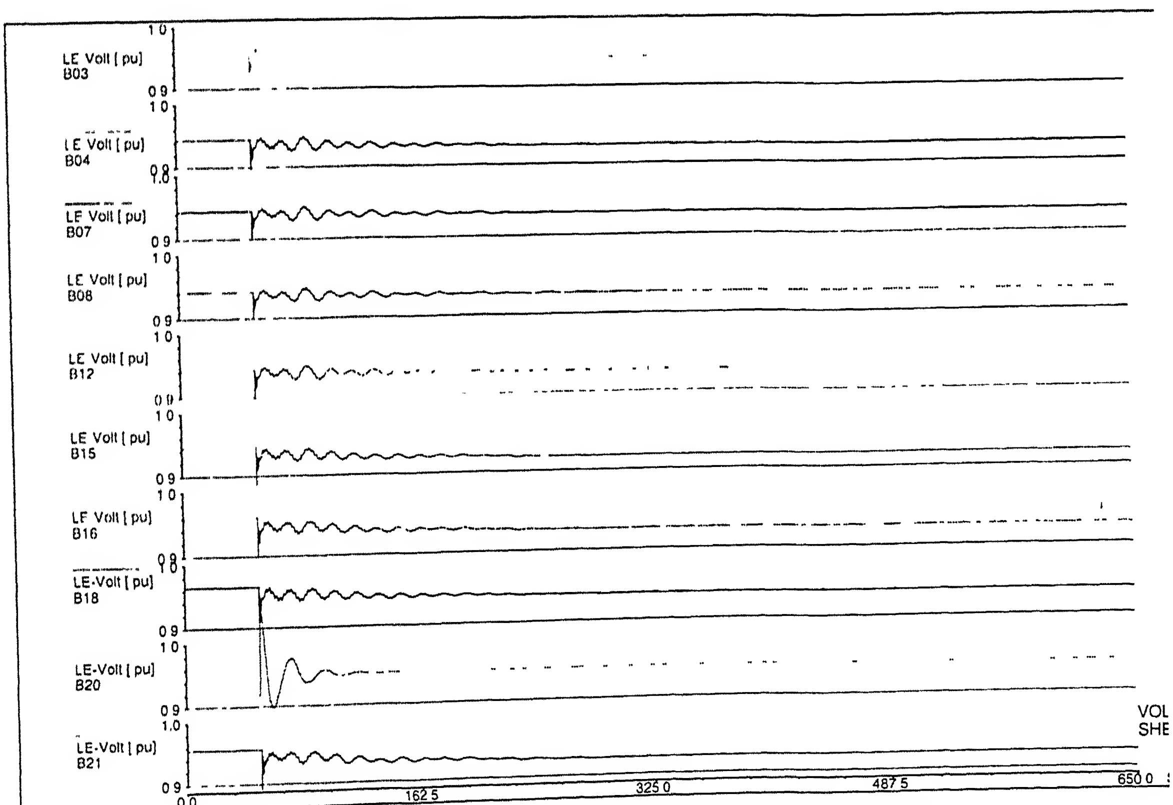

Figure 3.31 Voltages at load bus with ***GDLM with OXL***

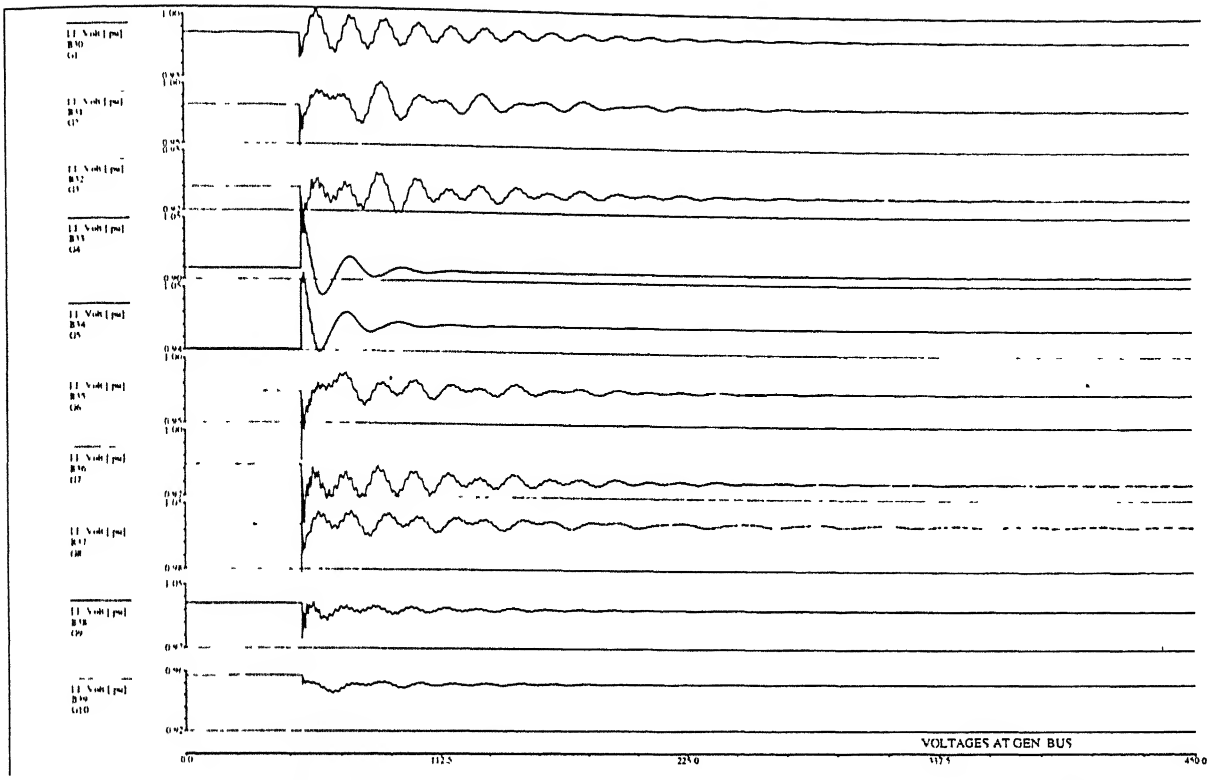

*Figure 3.32 Generator terminal voltages for **GDLM load model w/o OXL***

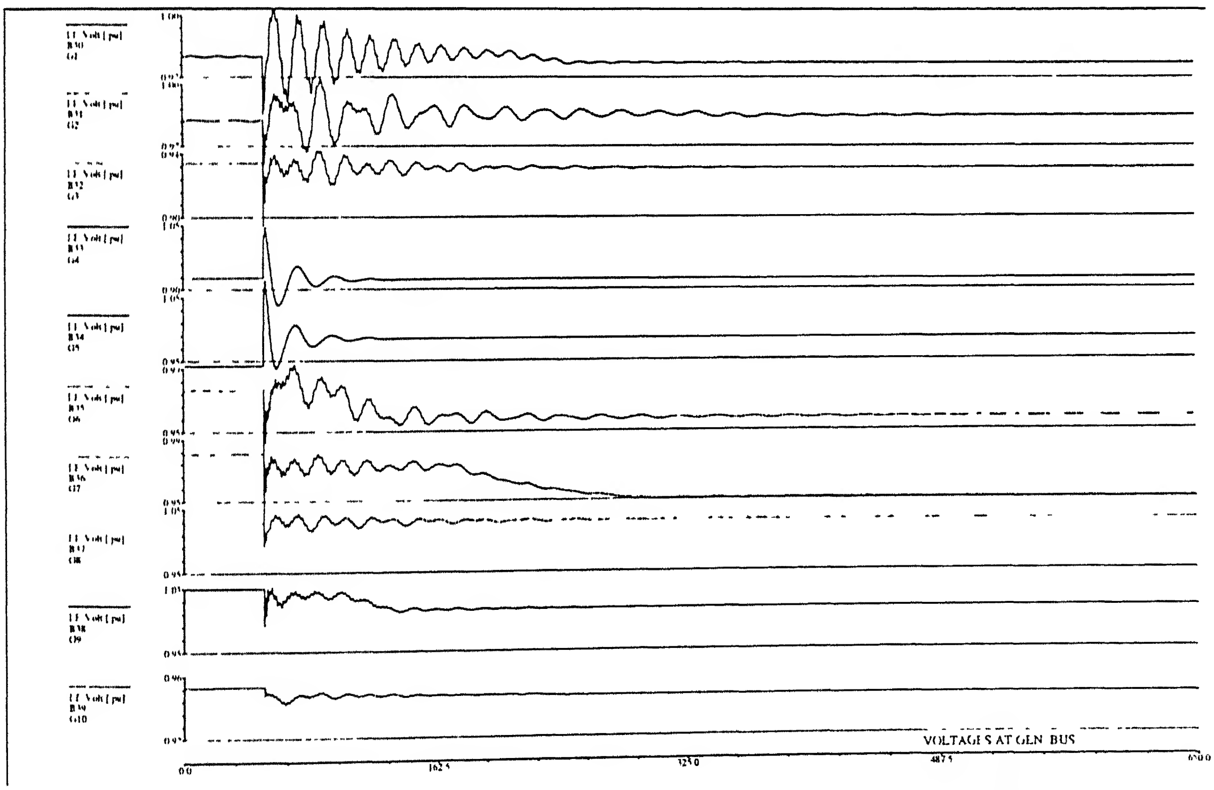

*Figure 3.33 Generator terminal voltages for **GDLM with OXL***

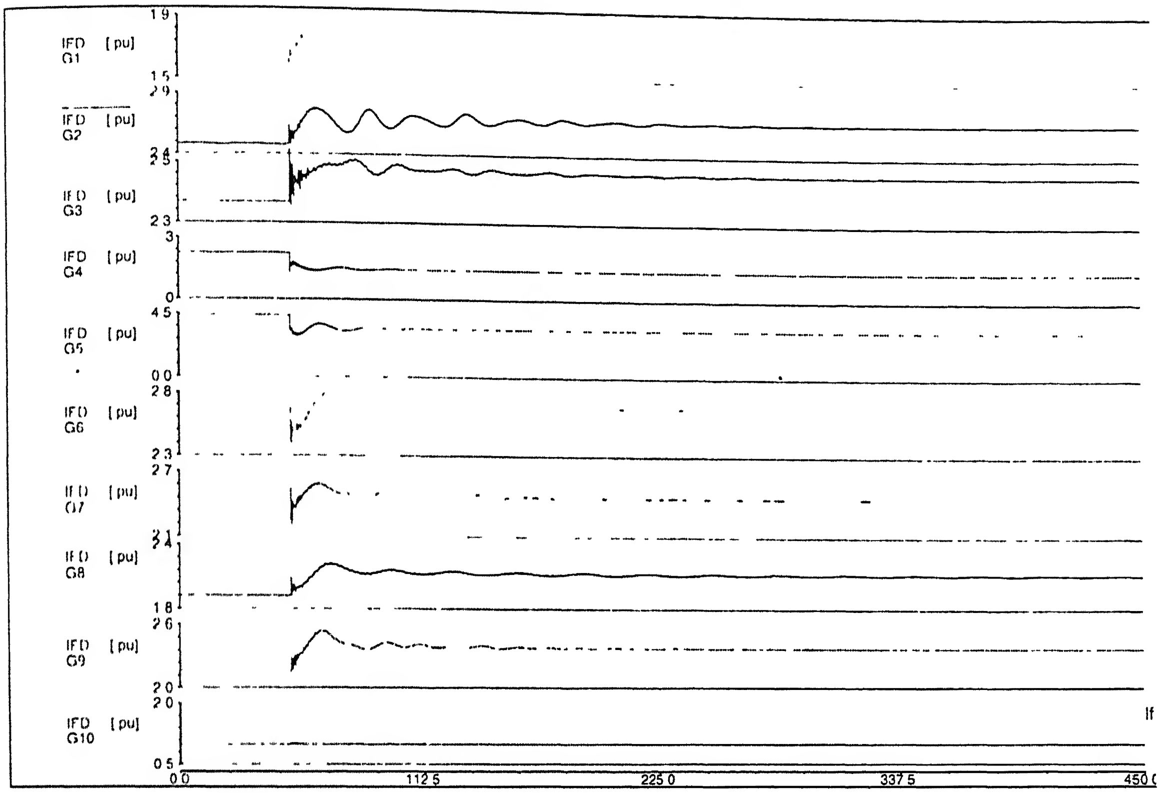

Figure 3.34 Field current of generators with ***GDLM load model*** *w/o OXL*

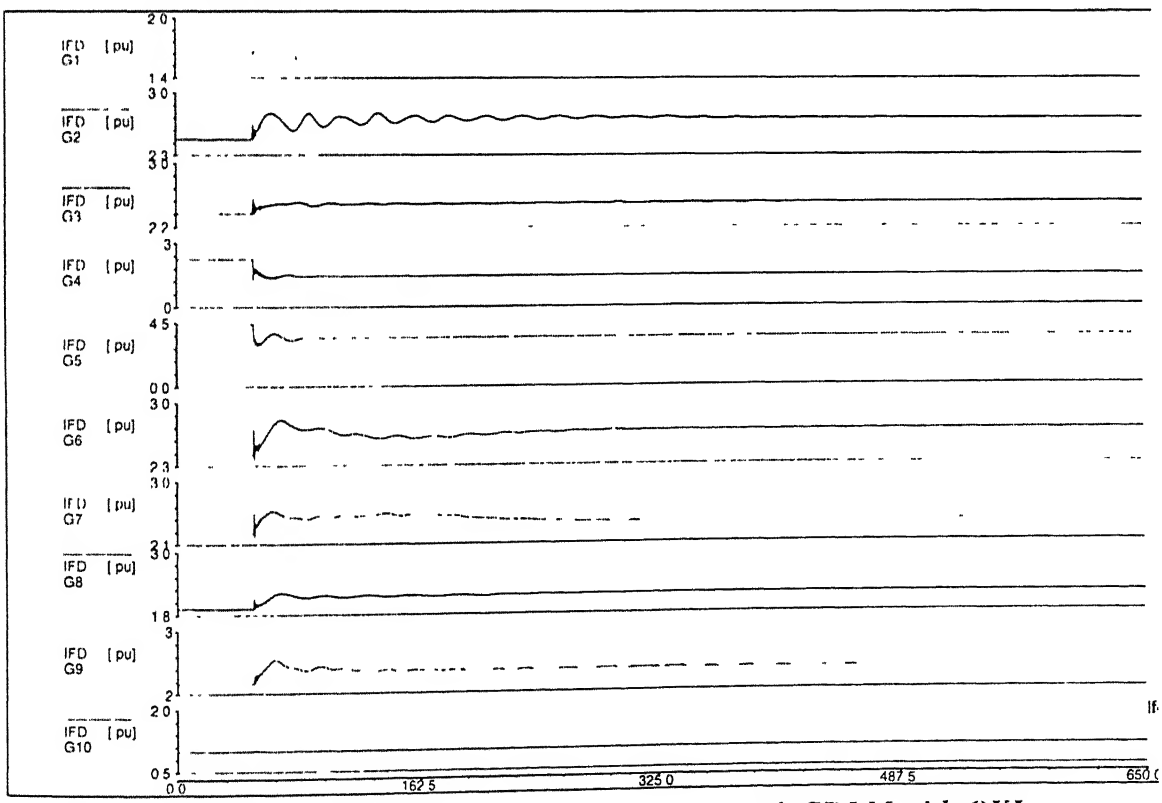

Figure 3.35 Field current of generators with ***GDLM with OXL***

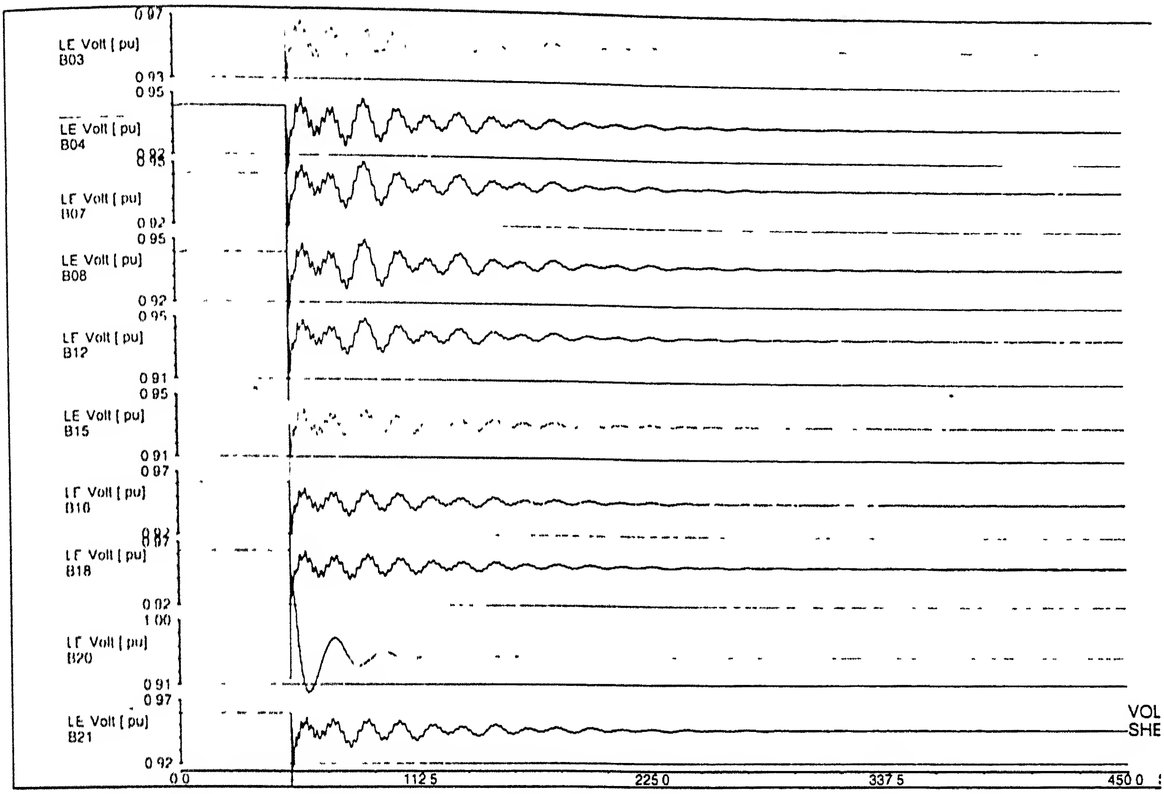

Figure 3.36 Voltages at load bus with ***GDLM load model w/o OXL***

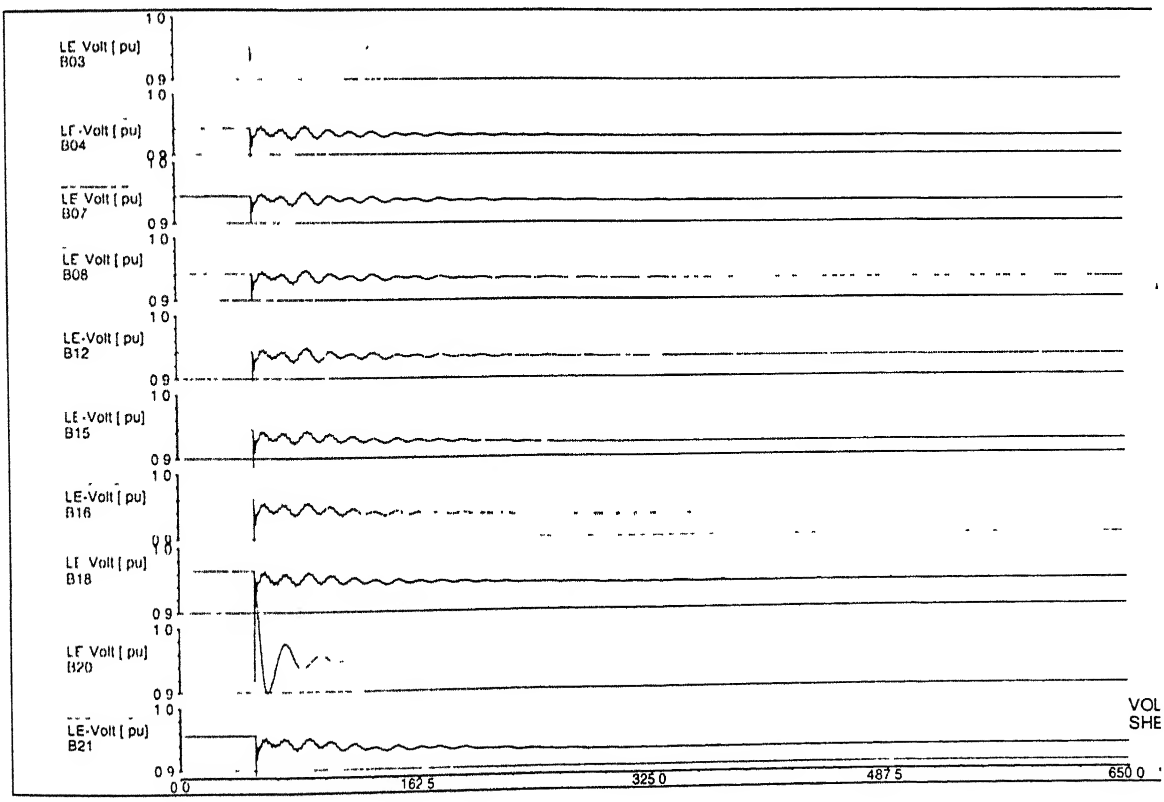

Figure 3.37 Voltages at load bus with ***GDLM load model w/o OXL***

the line is to cause the system voltage to drop initially. The terminal voltage of the generator is maintained by the AVR. The reactive power output of all the generators increase and all the load bus voltages settle at values slightly below the predisturbance values. The system is voltage stable.

<u>**Case 2 and Case 3:**</u>

In case 2 and case 3, the response of the system is more or less similar to the case 1 and system is voltage stable. The time response can be seen in the figures 3.20 to 3.23 for the case 2 and figures 3.24 to 3.27 for the case 3.

a) With OXL

This case was studied with all the three load models. However, results obtained with the generic dynamic load model only are presented. The time response can be seen in figures. 3.28 to 3.31. In this case, the reactive power demand at Gen. 1, 6, 7 and 9 is higher and field current of the generators exceed the maximum allowable limit. The over excitation limiter of all the generators start ramping the field current down. The generator 1 hits its limit at 200 sec, generator 6 at 100 sec, generator 7 at 160 sec and generator 9 at 90 sec. This results in the following

- The terminal voltage of above four generators, which is no longer being controlled by AVR, drops.
- Voltage at all the load buses drop.
- Voltages at load buses settle at values well below the predisturbance values.

Figures 3.32 to 3.39 show the comparison of the system response with OXL and with out OXL.

3.3 Conclusion

In this chapter, the impact of slower acting devices such as transformer load tap changer (LTC) and generator over excitation limiter (OXL) was studied on the 11-Bus test system and 39-Bus New England system. The long term dynamic simulation

results obtained for the three load models and the different load levels provide the following conclusions.

I. Without considering the over excitation limiter (OXL), the system remains voltage stable. However, the voltage collapse is observed considering the effect of the generator OXL in the simulation.

II. In some loading cases, where the system remains voltage stable even after considering the effect of OXL, the bus voltage settle to relatively lower value as compared to the corresponding situation without OXL.

III. To some extent, the action of ULTC helps in recovering the voltage. But after a threshold value, depending on the system loading and the action of the other controllers, its reverse action takes place. This accelerates the process of voltage collapse.

IV. The voltage instability and collapse scenario due to operation of OXL and reverse action of ULTC becomes more severe for increased loading value in the system.

V. The impact of the load types at all the load levels in terms of voltage value and load power were found to be same as observed in chapter 2.

CHAPTER 4

CONCLUSIONS

This thesis had mainly addressed to study the voltage stability and collapse phenomena based on long term dynamic simulation. The thesis had considered the impact of some of the slow acting devices such as generator over excitation limiter (OXL) & transformer under load tap changer (ULTC) actions in the simulation studies. In addition, the impact of various load models and load levels on voltage instability was also considered. The three types of load models considered were

1. 100 % Constant Active & Reactive Power (CARP) model.
2. ZIP load model (a general static load model).
3. Generic dynamic load model (GDLM).

From the results obtained on 500 kV, 11-bus test system and 39-bus New England test system, following main conclusions can be drawn :

I. In the case of any contingency, when voltage dip in step, the active and reactive component of load power in case of GDLM recovers after sometime and settles at relatively higher value as compared to ZIP load model and CARP load model.

II. After line outage, the steady state load bus voltage settles at lowest value in the case of GDLM, followed by ZIP and CARP load models.

III. Voltage stability analysis largely depends on the consideration of OXL dynamics. Without considering the OXL, the system remains voltage stable. However, voltage collapse is observed in the same system with consideration of OXL

IV. In some cases with the consideration of OXL, the system is voltage stable. However bus voltage settles to relatively lower value as compared to the corresponding case without consideration of OXL.

V. It was also observed that the OXL of the three generators in New England system operate at considerable different time instants. In order to improve voltage stability situation, the OXL of all the generators should operate almost at the same time instant. This can be ensured by generation rescheduling.

VI. The dynamics of ULTC is also very important in voltage stability analysis. In general, the action of ULTC helps in maintaining the load bus voltage constant. But in some situation, its reverse action takes place. This accelerates the voltage collapse. In practice to prevent voltage collapse due to reverse action of ULTC, its operation should be blocked.

VII. Loading level is also very important in voltage stability analysis. The voltage instability and collapse scenario becomes more severe for increased loading value in the system.

As a result of the work presented in this thesis, following future scope of research work are identified.

A. In this thesis, we have considered only first order generic dynamic load model. To simulate oscillatory behavior in the load recovery, higher order model is required.

B. This thesis has not addressed to the static aspects of voltage stability study. Dynamic analysis does not readily provide information regarding the sensitivity or degree of instability. These may make dynamic analysis impractical for examination of a wide range of system conditions or for determining stability limits unless combined with other techniques such as eigen value analysis.

C. For The New England test system, outage of only one transmission line has been considered. However outages of other lines and generators can be studied.

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Appendix A

Data For 11-Bus Test System

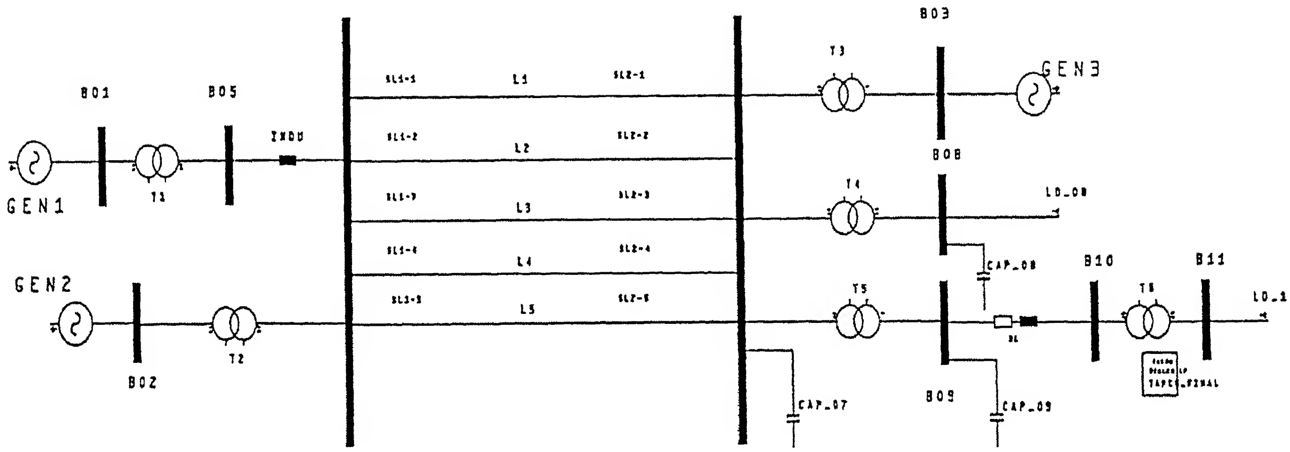

Figure A.1 Single line diagram of test bus system

The Test system data are as follows:

Table A.1 : Transmission Line data (R , X and B in pu on 100 MVA Base)

Line	R	X	B
5-6	0.0000	0.0040	0.0000
9-10	0.0010	0.0030	0.0000
6-7	0.0015	0.0288	1.1730

Table A.2 :Transformer Data (R and X in pu on 100 MVA Base)

Transformers	R	X	Ratio
T1	0.0000	0.0020	0.8857
T2	0.0000	0.0045	0.8857
T3	0.0000	0.0125	0.9024
T4	0.0000	0.0030	1.0664
T5	0.0000	0.0026	1.0800
T6	0.0000	0.0010	0.9750

Table A.3 : Generator data

Generator	P(MW)	V(pu)	
G1	Slack	0.9800	Load level 1
	Slack	0.9800	Load level 2
	Slack	0.9800	Load level 3
	Slack	0 9800	Load level 4
G2	1736	0.9646	Load level 1
	1736	0.9646	Load level 2
	1736	0.9646	Load level 3
	1736	0.9646	Load level 4
G3	1154	1.0400	Load level 1
	1154	1.0400	Load level 2
	1154	1.0400	Load level 3
	1154	1.0400	Load level 4

Table A.4 Load Bus Data

Load level	Bus 08		Bus 11	
	MW	MVAR	MW	MVAR
1	3320	1030	3435	985
2	3365	1058	3480	1010
3	3385	1090	3500	1030
4	3395	1100	3530	1040

Excitation system Data :

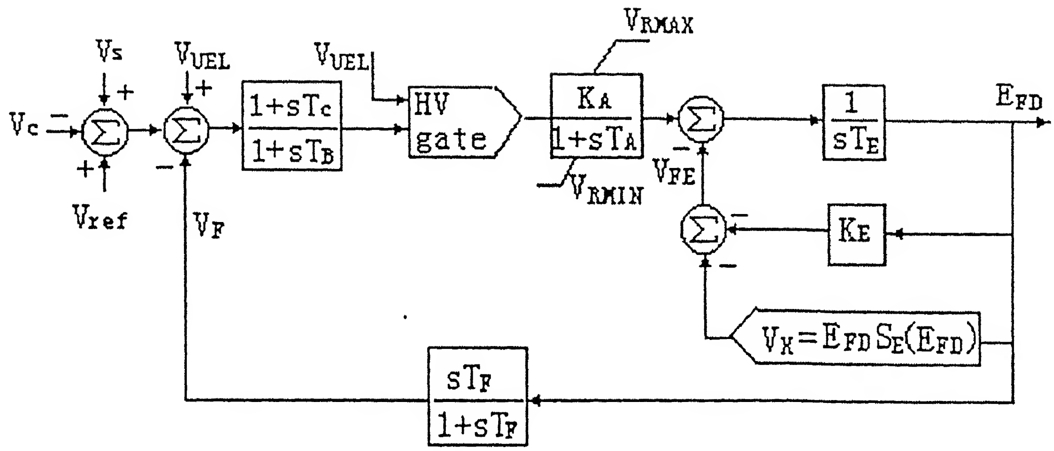

Figure A.2 DC 1A Excitation system of the generator

KA	*AVR:amplification*
TA	*AVR: time constant*
VRMAX	*AVR: upper limit*
VRMIN	*AVR. lower limit*
KE	*Exciter: amplification factor*
TE	*Exciter: time constant*
KF	*Excitation stabilizer: amplification factor*
TF	*Excitation stabilizer: time constant*

Data of Tap changer :

Time delay for the first tap movement : 30 Sec
Time delay for subsequent tap movement : 5 Sec
Dead Band : +- 1% pu bus voltage
Tap range : +-16 steps
Step size : 5/8 %(=0.00625 pu)

Appendix B

Data For 39-Bus New England Test System

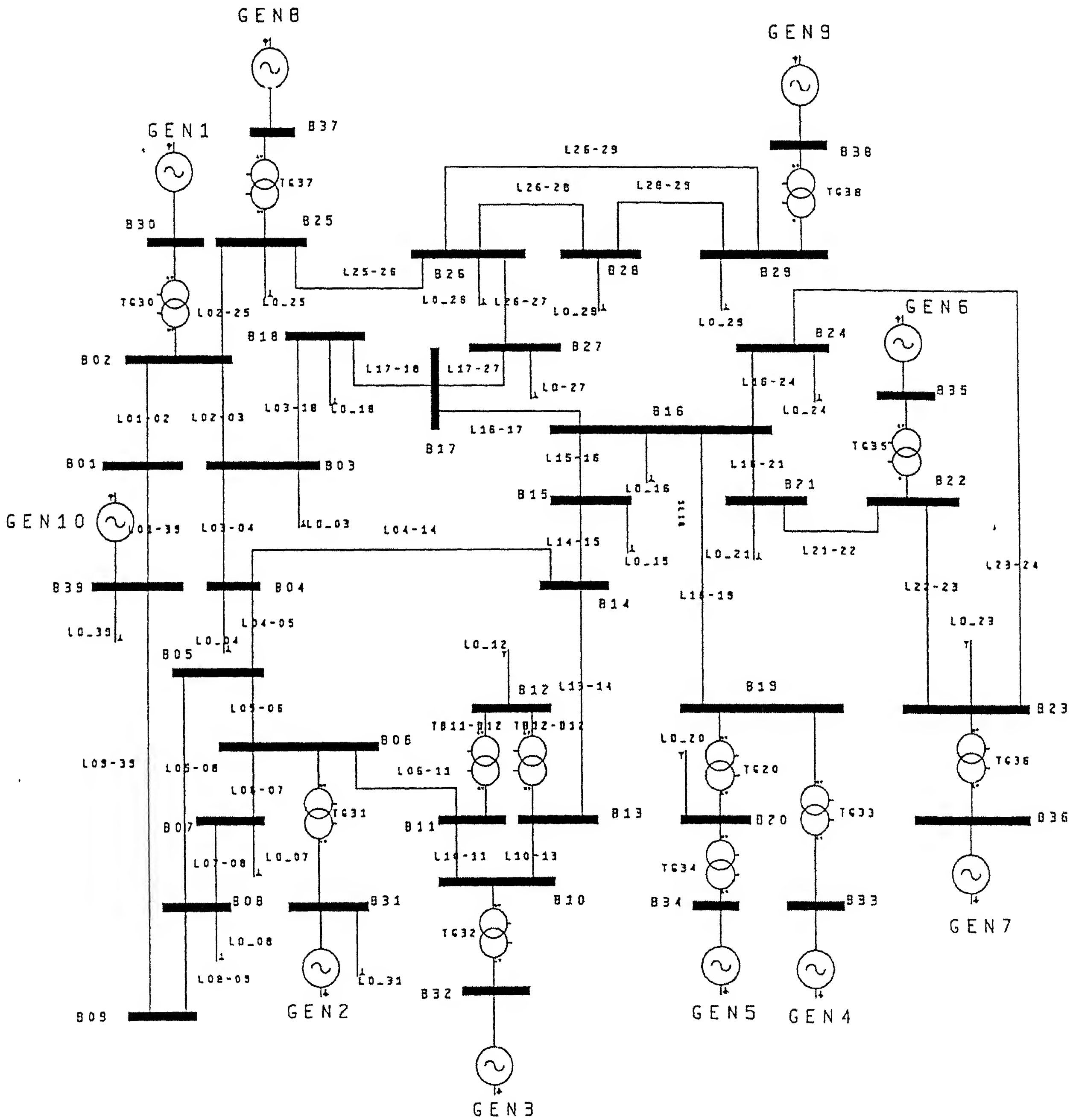

Figure B.1 Single line Diagram of New England Test Bus System

Table B.1 : Generator Data

Bus no.	Generator	MW	Mvar
B30	G1	850	144.92
B31	G2	573	207.11
B32	G3	650	205.74
B33	G4	632	108.94
B34	G5	508	166.99
B35	G6	650	211.12
B36	G7	560	100.44
B37	G8	540	0.654
B38	G9	830	22.663
B39	G10	1000	87.885

Table B.2 : Load Bus Data

Bus No.	Load	
	MW	MVAR
B03	322	2.4
B04	500	184
B07	233.8	84
B08	522	176
B12	8.5	88
B15	320	153
B16	329	32.3
B18	158	30
B20	680	103
B21	274	115
B23	247.5	84.6
B24	308.6	-92.2
B25	224	47.2
B26	139	17
B27	281	75.5
B28	206	27.6
B29	283.5	26.9
B31	9.2	4.6
B39	1104	250

Table B.3 : Transformer Data

Tran No.	From Bus	To Bus	Series impedence		Tap setting
			R p.u	X p.u	
TG1	02	30	0.0000	0.0181	1.025
TG2	06	31	0.0000	0.0250	1.070
TG3	10	32	0.0000	0.0200	1.070
TG4	19	33	0.0070	0.0142	1.070
TG5	20	34	0.0090	0.0180	1.009
TG6	22	35	0.0000	0.0143	1.025
TG7	23	36	0.0050	0.0272	1.000
TG8	25	37	0.0060	0.0232	1.025
TG9	29	38	0.0080	0.0156	1.025
TB12-11	12	11	0.0160	0.0435	1.006
TB12-13	12	13	0.0160	0.0435	1.006
TB19-20	19	20	0.0070	0.0138	1.060

Table B.5 : Line Data

Line No.	From Bus	To Bus	Series Impedence		Shunt capacitance nF/km
			Resistance Ohm/km	Reactance Ohm/km	
01-02	01	02	4.17	48.92	1.56E3
01-39	01	39	1.19	29.76	1.67E3
02-03	02	03	1.55	17.97	0.57E3
02-25	02	25	8.33	10.24	0.33E3
03-04	03	04	1.55	25.35	0 49E3
03-18	03	18	1.31	15.83	0.48E3
04-05	04	05	0.95	15 24	0.30E3
04-14	04	14	0.95	15.35	0.31E3
05-06	05	06	0.24	3.09	0.10E3
05-08	05	08	0.95	13.33	0.33E3
06-07	06	07	0.71	10.95	0.25E3
06-11	06	11	0.83	9.76	0.31E3
07-08	07	08	0.48	5.48	0.17E3
08-09	08	09	2.74	43.21	0.85E3
09-39	09	39	1.19	29.76	2.67E3
10-11	10	11	0.48	5.12	0.16E3
10-13	10	13	0.48	5.12	0.16E3
13-14	13	14	1.07	12.02	0.38E3
14-15	14	15	2.14	25.83	0.82E3
15-16	15	16	1.07	11.19	0.38E3
16-17	16	17	0.83	10.59	0.30E3
16-19	16	19	1.90	23.20	0.68E3
16-21	16	21	0.95	16.07	0.56E3
16-24	16	24	0.36	7.02	0.15E3
17-18	17	18	0.83	9.76	0.29E3
17-27	17	27	1.55	20.59	0.72E3
21-22	21	22	0.95	16.67	0.57E3
22-23	22	23	0.71	11.43	0.41E3
23-24	23	24	2.62	41.66	0.80E3
25-26	25	26	3.81	38.45	1.14E3
26-27	26	27	1.67	17.50	0.53E3
26-28	26	28	5.12	56.42	1.74E3
26-29	26	29	6.78	74.39	2.29E3
28-29	28	29	1.67	17.97	0 55E3